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IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF ALASKA

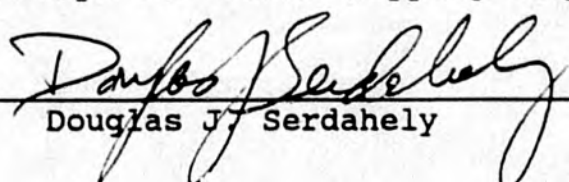
UNITED STATES OF AMERICA,	)	Civil Action No. A91-082 Civ.
	)	
Plaintiff,	)	
	)	
vs.	)	NOTICE OF LODGING BY EXXON
	)	CORPORATION AND EXXON SHIPPING
EXXON CORPORATION, EXXON	)	COMPANY OF SUMMARY REGARDING
SHIPPING COMPANY, ALYESKA	)	NATURAL RESOURCES
PIPELINE SERVICE COMPANY,	)	
AMERADA HESS PIPELINE	)	
CORPORATION, ARCO PIPE LINE	)	
COMPANY, EXXON PIPELINE	)	
COMPANY, MOBIL ALASKA PIPELINE	)	
COMPANY, PHILLIPS ALASKA	)	
PIPELINE CORPORATION, BP ALASKA	)	
PIPELINES, INC., UNOCAL ALASKA	)	
PIPELINE COMPANY, and the T/V	)	
EXXON VALDEZ, <u>in rem</u> ,	)	
	)	
Defendants.	)	
	)	
	)	
AND COUNTERCLAIM	)	
	)	

Please take notice that defendants Exxon Corporation and Exxon Shipping Company are lodging with the Court the attached summary and appended studies regarding natural resource injuries and recovery arising from the Exxon Valdez oil spill.

These materials, which have been publicly available for some time, are lodged to assist the Court in evaluating the pending consent decree and to provide the Court with information which both supplements and contrasts with views contained in the government summary of effects on natural resources filed on April 8, 1991.

DATED this 16th day of April, 1991.

BOGLE & GATES
Attorneys for Exxon Shipping Company

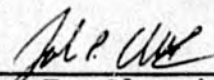
By: 

Douglas J. Serdahely

DATED this 16th day of April, 1991.

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WARREN CHRISTOPHER
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AFFIDAVIT OF SERVICE

STATE OF ALASKA)
 : ss.
THIRD JUDICIAL DISTRICT)

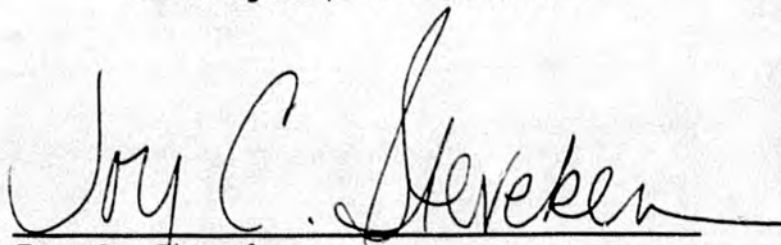
Joy C. Steveken, being duly sworn, upon oath, deposes and says: that she is employed as a legal secretary in the offices of Bogle & Gates, 1031 West 4th Street, Suite 600, Anchorage, Alaska 99501; that she has hand served or sent overnight delivery on April 16, 1991 the following document:

**Notice of Lodging by Exxon Corporation and
Exxon Shipping Company of Summary Regarding
Natural Resources**

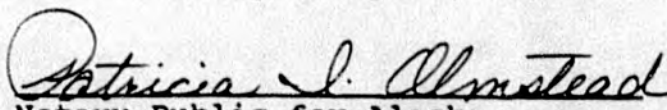
upon:

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222 West Seventh Avenue, #9
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William Brighton, Esq.
Environment Enforcement Section
Environment and Natural
Resources Division
Room 1541 (EES Dockets)
U.S. Department of Justice
Main Justice Building
Tenth and Pennsylvania
Ave., N.W.
Washington, D.C. 20530


Joy C. Steveken

SUBSCRIBED AND SWORN to before me
this 16th day of April, 1991.


Notary Public for Alaska
My Commission Expires: 5-11-93

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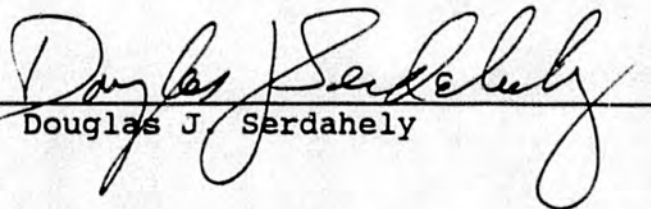
STATE OF ALASKA,	)	
	)	
Plaintiff,	)	
	)	
vs.	)	Case No. A91-083 Civil
	)	
EXXON CORPORATION, a New Jersey	)	
corporation, and EXXON SHIPPING	)	
COMPANY, a Delaware corporation,	)	
	)	
Defendants.	)	
	)	
_____	)	
AND COUNTERCLAIM	)	
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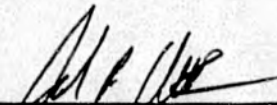
BOGLE & GATES
Attorneys for Exxon Shipping Company

By: 
Douglas J. Serdahely

DATED this 16th day of April, 1991.

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CLOUGH & ASSOCIATES

WARREN CHRISTOPHER
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By 
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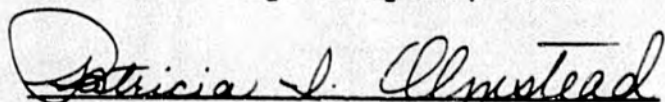
**Notice of Lodging by Exxon Corporation and
Exxon Shipping Company of Summary Regarding
Natural Resources**

upon:

Barbara Herman, Esq.
Craig J. Tillery, Esq.
Assistant Attorneys General
State of Alaska
Department of Law
1031 West Fourth Avenue
Suite 200
Anchorage, Alaska 99501


Joy C. Steveken

SUBSCRIBED AND SWORN to before me
this 16th day of April, 1991.


Notary Public for Alaska
My Commission Expires: 5-11-93

BOGLE & GATES

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SUMMARY OF PUBLISHED STUDIES ON THE EFFECTS OF THE EXXON VALDEZ OIL SPILL ON NATURAL RESOURCES

April 16, 1991

Introduction

Following the grounding of the Exxon Valdez on March 23-24, 1989, Exxon commissioned scientific studies for publication on the consequences of the oil spill. These studies have been available to the public for some time and now form the bases for this summary. These and other published studies describing the state of the ecology in the affected area demonstrate, among other things, that the water is clean, fish are abundant and safe to eat, and wildlife is thriving. Taken together, these studies characterize the robust state of recovery of the area affected by the oil spill.

This summary addresses broad categories of natural resources by providing the conclusions reached by the named scientists and by appending full copies of their studies, which have been publicly available for sometime.

Water is Clean

Effects of the oil spill on the waters of Prince William Sound and the western Gulf of Alaska are of critical importance to Alaskans and visitors. They provide a habitat for large commercial and recreational fisheries and a source of subsistence foods for native villagers. Recognizing its significance, immediately following the spill a water quality study of unprecedented scope was begun. The study, conducted by five leading environmental assessment firms and led by Dr. Jerry Neff, provided a concise evaluation of water quality in the affected area in the months following the spill.

Results from over 5000 water analyses, covering the period from March 1989 through March 1990, indicated the average concentrations of potentially hazardous hydrocarbons in the water remained well below State of Alaska standards. Furthermore,

"A comparison was made of the measured VOA (Volatile Aromatic) and PAH (Polycyclic Aromatic Hydrocarbon) concentrations in the water column and on the water surface (in sheens) of Prince William Sound with the published literature on the toxicity of petroleum to marine organisms, particularly Alaskan species. Average concentrations of petroleum hydrocarbon . . . are well below (approximately 10 to more than 1000 times below) concentrations that have been shown to be toxic or cause harmful sublethal effects in marine animals." [1]

[] Technical references listed in Attachment A.

In summary, Dr. Neff concluded that,

"It is extremely unlikely that hydrocarbon concentrations resulting from the spilled oil have had or will have any adverse effects on plants and animals living in the water column of Prince William Sound and the western Gulf of Alaska, including commercial fishery species."

As noted below in the Fishery Resources section, subsistence foods were found to be safe to eat as would be anticipated based upon the results of the water quality study.

In response to public and agency concern about the sheens observed in Prince William Sound, Dr. Neff discussed a special sheen study in his report, conducted as part of the overall water quality effort. As background, Dr. Neff provided technical detail on sheens (i.e., their typical thickness and how their color indicates thickness), noting that they are very thin. For example, a sheet of paper is typically 450 times thicker than a rainbow-colored sheen. He also noted that a tablespoon of oil would form a sheen of 625 square feet. Further, he stated,

"Oil sheens are patchy, short-lived phenomena in western parts of Prince William Sound. Surface waters covered with oil sheens derived from spilled oil washing off oiled shores contain low concentrations of highly weathered oil (crude oil which has lost its lighter, more toxic components)."

He further reported that,

"Crude oil is not the only source of sheens in Prince William Sound. Natural organic material from decaying vegetation or from heavy schooling of some fish, such as herring, can cause sheens that are difficult to distinguish from oil."

He also noted that National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service had revealed that some Prince William Sound fisheries closed in 1989 because of sheens which were later shown to be caused by bilge oil, diesel oil, and hydraulic fluid -- not Valdez crude oil. He also observed that by late summer 1990 sheen monitoring reports showed that only a small percentage of the sheens observed were identified to be from the spill. He concluded,

"It is unlikely that marine organisms in Prince William Sound are being adversely affected by sheens of spilled oil."

Habitat Recovery is Well Underway

The biologic habitat most acutely affected initially by the spill were those shorelines impacted by floating oil. The cleanup program conducted by Exxon in 1989 and 1990 under the direct supervision and approval of the U. S. Coast Guard, which incorporated advice of various federal, state, and local entities, dealt directly with the shoreline. The cleanup program on which Exxon has expended more than \$2 billion was, like the water evaluation,

unprecedented in its extent. [19,20] Exxon's successful cleanup program along with the widespread use of bioremediation techniques hastened the restoration and recovery process.

Several observers have noted the obvious extent of nature's recovery. Drs. J. M. Baker, R. B. Clark, and P. F. Kingston in describing the biological recovery of shorelines in April and September, 1990, noted:

"Only a portion of the shoreline had been oiled (by the spill in 1989) and, as with most other oil spills, the bulk of the damage had disappeared during the first year. The area has retained its natural beauty; there are abundant signs of plant and animal life, and recovery is well under way on even the most severely impacted beaches." [17]

"The summer settlement and growth of the organisms we saw was good biological evidence that the sea and the shores were clean enough for recovery to take place. Mussels, barnacles and rockweed that were abundant on the shores as newly settled juveniles in Spring had become established as young adult populations by the Fall. Such development had taken place even where there had been no clean-up or there was still residual oil on the shore." [2]

This observation of recovery was confirmed by a July 5, 1990, NOAA report which found:

"there was evidence of recolonization of biological communities and that the small amounts of remaining subsurface oil were not causing a serious impact on the environment." [3]

Dr. E. H. Owens has monitored recovery of the oiled shorelines since 1989. In spite of focusing on a set of study sites which were biased toward worse-case conditions, Owens found

"The combined result of treatment and natural cleaning was that the majority of shorelines retained little or no oil by the end of the summer of 1990 . . . The combined average surface oil cover area of all the Prince William Sound study sites dropped drastically between May 1989, from 46 percent of the total observed area to less than 2 percent by September 1990." [6]

With respect to the general nature of recovery of shoreline biologic communities, he observed,

"Key organisms were observed to be similar in abundance and distribution on most oiled and non-oiled sites in September 1990." [6]

In its consideration of 1991 cleanup requirements, NOAA stated, ". . . even where there is direct contact with weathered oil, intertidal organisms have shown remarkable recovery," in a report released to the Coast Guard on March 15, 1991. [4]

NOAA further observed in its report on its 1990 Shoreline Monitoring Program that, "Evidence of intertidal recovery was observed at all impacted sites." [5]

Fishery Resources are Abundant, Productive, and Safe to Eat

The Alaska fisheries support the state's second largest economic component, second only to the oil industry. As such, the potential impacts of the spill on fishing resources required evaluation. The water quality study provides strong evidence that those resources were virtually unaffected. Perhaps, the most persuasive indications of the viability of the resource are the record 1990 harvests of pink salmon and herring, the two most significant commercial fish in Prince William Sound. Over 44 million pink salmon were caught (51 percent of the state's total), far exceeding the prior record of 29 million fish. Similarly, approximately 8300 tons of herring, more than the entire year's "harvest quota," were caught in a 20 minute period although the season typically lasts several hours. Early reports on the 1991 herring fishery indicate another highly successful season.

Further, a number of experts have directly assessed the potential spill effects and have confirmed the view that impacts are likely minimal and the fisheries resources remain safe for human consumption. Royce, et al, in assessing the condition of the fisheries resources, stated that,

"The potential long-term impact of the oil spill on fish is under careful study, but it is unlikely that any significant adverse effects on finfish populations will be discovered. Throughout 1989 and 1990, there were no confirmed reports of large fish mortalities, oil tainting, or contamination of commercial seafood products from the spill. In addition, long-term damage to finfish has not been documented in the hundreds of studies of earlier oil spills -- many of which were larger than the Exxon Valdez spill." [8]

Minerals Management Service (MMS) of the Department of Interior has summarized the results of studies of Exxon Valdez spill effects on herring in Prince William Sound. Robert M. Meyer with MMS delivered a paper to the International Herring Symposium in Anchorage in October 1990 noting,

"Results from studies of herring eggs and larvae conducted following the Exxon Valdez oil spill indicated that the presence of spilled oil had no measurable effect on hatching success, occurrence of abnormal larvae, or larval growth and mortality rates (McGurk, 1990 a, b). These results suggest that the developing eggs and resulting larvae were exposed to levels of dissolved and dispersed oil less than that needed to elicit an acute response, i.e., death, deformity, or reduced growth rates." [7]

In commenting on the risks associated with an oil spill near Port Moller, MMS pointed out,

"... the observation that spawning populations of Pacific herring are found in areas where chronic hydrocarbon pollution is endemic, i.e., San Francisco Bay, Pudget (sic) Sound, etc. suggests that herring populations are able to tolerate exposure to sublethal concentrations of hydrocarbons that exceed those expected to occur (sic) in Port Moller following an offshore oil spill."

This observation is obviously applicable where there is a transitory exposure, as was the case with the Valdez spill.

The NOAA report of March 15, 1991, found no evidence of residual oil causing sublethal effects by progressing up the foodchain. Results from their 1990 Shoreline Monitoring Program noted,

"Chemical analyses of tissues from selected intertidal organisms indicated accumulation of hydrocarbons from the environment but no evidence of magnification through predator-prey interactions." [5]

Both NOAA and the Food and Drug Administration (FDA) have tested the safety for human consumption of subsistence foods (particularly salmon, bottomfish, and shellfish; but including seals, deer, ducks, and sea lions). Neither agency has identified unsafe foods from the impacted areas. [9]

Wildlife is Abundant and Thriving

With respect to seabird impacts, it is important to understand there are about 67 million birds in the Gulf of Alaska and Prince William Sound (NOAA, "The Gulf of Alaska, Physical Environment and Biological Resources", 1986). While the spill caused initial mortality of seabirds, the populations remain abundant. Moreover, the spill mortalities are well within the range of impacts frequently sustained by seabird populations due to natural events and chronic pollution without apparent long-term detriment. Drs. Baker, Clark, and Kingston note,

"Seabirds are among the most conspicuous casualties of oil slicks and, as such, attract considerable public attention. But there is no reason to suppose that, from a biological point of view, this mortality is damaging to seabird populations. Arctic and sub-Arctic seabirds also suffer heavy mortality from natural causes and from fishery practices. Even the auks (family including murre), which because of their very low reproductive rate might be expected not to be able to make good these losses, have sustained their population; and there is no evidence that other seabirds with a greater reproductive potential have declined in numbers." [16]

Eagles and sea otters were the subject of much public concern after the spill. While both species suffered initial mortalities, there are strong indications that both are recovering quickly and thriving. [12,14] M. J. Gibson and Dr.

J. White, who worked on eagle and bird rehabilitation in 1989 and visited Prince William Sound in 1990 reported,

"accumulating evidence indicates the area's eagle population is generally healthy and thriving" [11]

Moreover,

"We observed numerous eaglets and recent fledglings throughout the area. In 1990, many pairs were not only occupying previously oiled territories, but they had also nested, laid eggs, incubated, and hatched chicks that had developed normally." [11]

With regard to sea otters, the observations in 1990 are also encouraging. More than 16,000 sea otters inhabited the portions of Prince William Sound and the Gulf of Alaska that were impacted by the oil according to A. R. DeGange in a U.S. Fish and Wildlife Service symposium in April 1990. Drs. T. M. Williams and R. W. Davis, who organized and worked in Exxon's otter rehabilitation program in 1989, visited Prince William Sound in 1990 to gauge the recovery of the otters in impacted areas. [10] From their observations they noted,

"Large numbers of adults and pups were found in previously oiled areas, and they appear to feed and behave normally. These results suggest that many of the previously contaminated areas are able to support sea otters." [13]

Drs. Baker, Clark, and Kingston also commented on the recovery of sea otter populations,

"Sea otters are abundant in Prince William Sound. With a potential for the population to grow at nearly 20% per year, we have concluded that whatever losses suffered in the oil spill are likely to be rapidly made good by natural reproduction." [2]

Ecological Overview

These observations on individual species and habitats are indicative of the health of the overall ecosystem in Prince William Sound and the Gulf of Alaska. Drs. Baker, Clark, and Kingston have commented on the relative rate of ecological recovery from their perspective which reflects the study of numerous past spills. They note,

"There is a wealth of information about the recovery of cold water marine ecosystems following oil spills in various parts of the world. In all cases recovery events have been similar to those seen in Prince William Sound. If anything, because of the exceptionally thorough clean-up measures and natural cleaning processes, biological recovery has started sooner and proceeded further in Alaska than might have been anticipated." [2]

Dr. A. W. Maki, Exxon's lead environmental scientist on the Valdez spill, integrated the observations on parts of the ecosystem into an overall

assessment in his article in Environmental Science and Technology. Among his findings he noted,

"Field counts of plants, fish, and mammals from throughout the spill area provide convincing data that wildlife species are surviving and reproducing, thus confirming that biological recovery is rapidly taking place." [15]

Recovery Consistent with Historical Observations

The quick and robust recovery of Prince William Sound and the Gulf of Alaska is consistent with scientific observations made following previous spills over the last 25 years. Dr. J. E. Mielke summarized the technical literature on spills in his 1990 Congressional Research Service report, "Oil in the Ocean: The Short- and Long-Term Impacts of a Spill." He found,

"Short-term impacts on marine animal life are dramatic but recovery of species populations in almost every case studied has been swift." [18]

The recovery in Prince William Sound and the Gulf of Alaska conforms to this pattern. Drs. J. M. Baker, R. B. Clark, and P. F. Kingston have personally worked on many previous spills; they visited spill impacted areas in April and September, 1990, to assess the recovery in comparison to previous spills. They found,

"Our examination of the spill area confirmed our expectations, based on knowledge gained from previous accidents, that natural recovery is proceeding in Prince William Sound and the Gulf of Alaska. We expect the recovery to continue and to be relatively rapid." [17]

"Although isolated patches of weathered oil may still be found, nearly all of the beaches in Prince William Sound and the Gulf of Alaska are of clean appearance. Some small and isolated portions of the shoreline may retain oil for several years, but our investigations of previous oil spills indicate that the long-term impact on plants and animals should be minimal."

"The recovery process is well under way. Once started, if it is allowed to proceed without interruption, it will continue and be robust, as it has been following other spills throughout the world."

Cleanup is Essentially Complete

The cleanup of the spill is also in an advanced state. Little additional work remains to be done. The Owens report cited earlier clearly portrays the rapid disappearance of oil from the shoreline [6] and, as early as July 1990, NOAA noted that, "... deeply buried subsurface oil (i.e., oil beyond the reach of near-term bioremediation and other less-intrusive cleanup methods) poses little risk of causing further significant environmental injury." In addition, in its March 15, 1991 letter to the Coast Guard, NOAA stated,

"We are rapidly reaching the point of diminishing returns where the amount of effort, and the associated impacts, required to further reduce the total amount of oil remaining on, or in, a beach cannot be justified based solely on the assumption that the presence of oil poses a threat to the overall health of the local environment." [4]

In addressing the environmental threat of remaining oil, NOAA stated,

"The bulk composition of the remaining oil is comprised primarily of the residual or asphaltene fractions which have negligible solubility and little demonstrated toxicity, and thus pose little environmental risk to intertidal and water-column organisms, even if there were routine releases."

Given the minimum remaining oil, Drs. Baker, Clark, and Kingston addressed further cleanup from the perspective of those who have closely monitored past oil spills.

"There have been continuing public discussions about whether further clean-up of remaining oil on the beaches in Prince William Sound and the Gulf of Alaska is necessary." [2]

"Whether or not further clean-up measures to remove this residual oil are justified largely depends on the human use a beach is put to. Our judgement is that where recovery of animal and plant life is already well established, the residual oil is obviously doing no harm and the organisms established on the shore will hasten the final removal and degradation of the oil residues."

Conclusion

The extensive cleanup program conducted by Exxon, in combination with natural processes, removed the threat of further injury to wildlife by direct contact, substantially restored the aesthetic appeal of the area, and facilitated biologic recovery, particularly in the heavily oiled areas. Furthermore, the studies summarized herein demonstrate a rapid recovery of the impacted resources.

Attachments

Attachment A
Technical References

Water

1. Neff, J. M. (Senior Consultant, A. D. Little). "Water Quality in Prince William Sound and the Gulf of Alaska." Cambridge, Massachusetts: Arthur D. Little; 37 pp.; March, 1991.

Habitat Recovery

2. Baker, J.M.(Independent consultant, former Director of U.K. Field Studies Council); Clark, R.B.(Prof. Emeritus of Zoology, University of Newcastle Upon Tyne); Kingston, P.F. (Asst. Director of U.K. Institute of Offshore Engineering). "Two Years after the Spill: Environmental Recovery in Prince William Sound and the Gulf of Alaska." Presented at American Association of Petroleum Geologists Convention; 31 pp.; Dallas, TX, April 7-10, 1991.
3. National Oceanic and Atmospheric Administration. "Excavation and Rock Washing Treatment Technology: Net Environmental Benefit Analysis. Compiled by the Hazard Materials Response Branch, National Oceanic and Atmospheric Administration, Seattle, Washington; Contributions from Exxon Company, U.S.A., National Oceanic and Atmospheric Administration, State of Alaska; Submitted to the United States Coast Guard, Anchorage, Alaska, July 9, 1990. 218pp.
4. National Oceanic and Atmospheric Administration. "NOAA Review of Status of Prince William Sound Shorelines Following Two Years of Treatment by Exxon." In: March 15, 1991, letter to RADM D. E. Ciancaglini by D.M. Kennedy.
5. National Oceanic and Atmospheric Administration. "Exxon Valdez Shoreline Monitoring Program: 1990 Results" Pentec Environmental, Inc. and Environmental and Energy Service Co. Released April 9, 1991, in Washington, D. C. by NOAA.
6. Owens, E.H. (Senior Consultant, Woodward-Clyde). "Changes in Shoreline Oiling Conditions 1-1/2 Years after the 1989 Prince William Sound Spill." Unpublished report. Seattle, Washington: Woodward-Clyde; 116 pp.; March, 1991.

Fish and Subsistence Recovery

7. Meyer, R.M. (U.S. Department of Interior Minerals Management Service). "Assessing the Risk to Pacific Herring from Offshore Gas and Oil Development in the Southeastern Bering Sea" Paper presented at the International Herring Symposium, Anchorage, Alaska, October 1990.
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**WATER QUALITY IN
PRINCE WILLIAM SOUND
AND THE
GULF OF ALASKA**

MARCH 1997

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Battelle Ocean Sciences

Dames & Moore

Kinnetic Laboratories, Inc.

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THE GULF OF ALASKA**

MARCH, 1991
(An update of the April, 1990 report)

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TABLE OF CONTENTS

Summary	iv
Water Quality in Prince William Sound and the Gulf of Alaska	
Introduction	1
Water Quality in Prince William Sound.....	3
Offshore Water Quality	3
Field Program	3
Petroleum Hydrocarbon Analysis.....	3
Analytical Results.....	4
Offshore Results Summary.....	11
Nearshore Water Quality	11
Field Program	11
Analytical Results.....	11
Nearshore Results Summary.....	15
Water Quality in the Gulf of Alaska.....	17
Field Program	17
Analytical Results.....	17
Gulf of Alaska Results Summary	19
Oil Sheens on the Water Surface.....	20
Introduction	20
Background.....	20
Composition and Environmental Significance	
of Crude Oil Sheens	21
Sheen Sampling and Analysis Summary.....	22
Summary of Water Quality in Prince William Sound	
and the Gulf of Alaska.....	23
Biological Effects of Crude Oil on Marine Organisms	
in Prince William Sound and the Gulf of Alaska.....	24
Introduction	24
Background.....	24
Biological Effects	25
Phytoplankton	25
Zooplankton.....	26
Fish.....	26
Conclusions of Biological Effects Studies.....	29
Literature Cited	30
Appendix	33
Updates to the April, 1990 Water Quality Report	33
Averaging Sets of Concentrations that Contain Values	
Below the Nominal Reporting Limit	33
Handling Nonrepresentative Data.....	34
Reprocessing of PAH Data	34
Analysis of Petroleum Hydrocarbons (PHC) and	
Total Petroleum Hydrocarbons (TPH) in Water	35

LIST OF FIGURES

Figure 1.	Station Locations in Prince William Sound Where Offshore Hydrocarbon Concentrations Were Measured.	2
Figure 2.	Crude Oil Hydrocarbon Groups.....	4
Figure 3.	Average Volatile Aromatic (VOA) Concentrations at Primary Offshore Sites in Prince William Sound	5
Figure 4.	Distribution of Volatile Organic Analyses (VOA) (Offshore Prince William Sound)	6
Figure 5.	Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations at Primary Offshore Sites in Prince William Sound	8
Figure 6.	Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations for Surface and Deeper Water at Primary Offshore Sites in Prince William Sound	9
Figure 7.	Distribution of Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Offshore Prince William Sound)	10
Figure 8.	Station Locations in Prince William Sound Where Nearshore Hydrocarbon Concentrations Were Measured	12
Figure 9.	Distributions of Volatile Aromatic (VOA) and Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Nearshore Prince William Sound)	14
Figure 10.	Station Locations In Western Gulf of Alaska Where Hydrocarbon Concentrations Were Measured	16
Figure 11.	Distributions of Volatile Aromatic (VOA) and Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Western Gulf of Alaska)	18
Figure 12.	Distributions of Polycyclic Aromatic Hydrocarbon (PAH) and Petroleum Hydrocarbon (PHC) Analyses in Sheens from Bays in October, 1989 (Western Prince William Sound)	21
Figure 13.	Distribution of Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Prince William Sound and Western Gulf of Alaska).....	23
Figure A-1.	Distributions of Petroleum Hydrocarbon (PHC) and Total Petroleum Hydrocarbon (TPH) Analyses (Offshore Prince William Sound)	35
Figure A-2.	Distributions of Petroleum Hydrocarbon (PHC) and Total Petroleum Hydrocarbon (TPH) Analyses (Nearshore Prince William Sound)	36
Figure A-3.	Distributions of Petroleum Hydrocarbon (PHC) Analyses (Western Gulf of Alaska).....	37

LIST OF TABLES

Table 1.	Approximate Thickness of Crude Oil on the Sea Surface Based on Appearance (Color)	20
Table 2.	Doses (Concentration Times Duration-of-Exposure) of Prudhoe Bay Crude Oil and Cook Inlet Crude Oil Causing 50 Percent Mortality in Several Species of Alaskan Marine Animals.....	28
Table 3.	Doses Based on a 96-Hour Exposure to Petroleum Hydrocarbons at Average Concentrations Measured in Prince William Sound	28
Table A-1.	Comparison of Numbers of Water Quality Analytical Results Available at the Time of the April, 1990 Report and in this March, 1991 Update	33

SUMMARY

This report describes detailed water quality measurements for Prince William Sound and the Gulf of Alaska taken over about a 12 month period following the *Exxon Valdez* oil spill. It significantly expands on material first presented in an April, 1990 report on the topic. Since publication of the April, 1990 report, the number of available water sample analyses has more than doubled, representing an expansion of coverage in both geographical area and time period. The extent of the water quality studies presented in this report is unprecedented in the oil spill literature. Conclusions presented are based on water analyses conducted using the best available methods; in some cases detection limits for these methods had to be substantially improved in order to detect the very low concentrations of hydrocarbons present.

The water quality investigations described in this report were undertaken to address concerns expressed about the effects the spill would have on the marine ecosystem of the Sound and the adjacent Gulf of Alaska following the crude oil spill in Prince William Sound on March 24, 1989. The marine plants and animals living in the intertidal zone of heavily oiled shores or on the water surface were, of course, immediately affected by direct contact with bulk oil. However, populations of plants and animals living below the water surface in the water column (the area between the ocean surface and above the sea floor) probably were not adversely affected, even after long periods of time, because measured concentrations of petroleum hydrocarbons in the water column have remained below toxic levels since the spill. There have been no verified mortalities or other adverse effects of the oil in animals living in the water column, including many commercial fishery species. Further, record salmon and herring fishing seasons were experienced in 1990.

This report contains a summary of the results of several studies on the distribution and concentrations of petroleum hydrocarbons in the water column, from the surface to depths of up to 42 meters (138 feet), and in surface oil sheens. It includes results of samples analyzed from areas where the spilled oil moved as well as areas not impacted by the spill, that served as reference sites. Samples were obtained at times when concentra-

tions should have been highest, immediately after the spill and following shoreline treatments, as well as up to about one year following the oil spill. These results are discussed with relation to information from the scientific literature on the toxicity of crude oil to marine organisms living in the water column.

The report published in April, 1990 summarized the results available at that time of extensive field surveys to monitor the concentrations of petroleum hydrocarbons in the water column of Prince William Sound in the months following the oil spill. Because of the large number of samples obtained and the time required to conduct the analyses, only about half of the samples taken had been analyzed and could be included in that report. Samples that were included covered the time period from March to October, 1989. More than 5,000 analyses of the concentrations of petroleum hydrocarbons in the water column of Prince William Sound and the western Gulf of Alaska, and more than 2,400 quality control samples are included in this update. The additional data available since the April, 1990 report include results of analysis for water samples collected in offshore waters of Prince William Sound in February-March, 1990, additional results for nearshore waters of Prince William Sound, and extensive data on water quality of offshore and nearshore waters of the western Gulf of Alaska in areas where some of the spilled oil drifted. In addition, some of the data discussed in the April report were reprocessed to make methods consistent among laboratories that conducted the analyses. This updated report includes a discussion of the April report data as well as the newly-available and reprocessed data.

Within a few days after the spill, Exxon engaged independent contract research organizations (Arthur D. Little Marine Sciences, Battelle Ocean Sciences, Kinnetic Laboratories, Inc., Dames and Moore, and an Alaskan firm, America North Inc.) to monitor the distribution, concentrations, and changes over time of petroleum hydrocarbons in the water column throughout Prince William Sound and the western Gulf of Alaska. Additional measurements were made of the concentrations and compositions of petroleum

hydrocarbons in surface sheens of weathered crude oil occasionally observed in the Sound.

Measured concentrations of petroleum hydrocarbons in the water column of Prince William Sound have been consistently low since measurements began in late March, 1989, about a week after the spill. For a brief period in April, in regions of the Sound where the oil spread, there was a measurable increase in the upper water column in the average concentrations of volatile aromatic hydrocarbons (VOAs) and polycyclic aromatic hydrocarbons (PAHs), the potentially toxic fractions of oil. Highest concentrations of PAH usually were in surface water samples that often contained floating sheen material. However, these slightly elevated concentrations were well below the State of Alaska standard for aromatic hydrocarbons in marine waters. Concentrations of petroleum hydrocarbons in the water column of a few heavily oiled, sheltered bays remained slightly above background through June, 1989. Concentrations of VOAs and PAHs remained low in the offshore and nearshore water column of the western Gulf of Alaska. Throughout most of the open waters of Prince William Sound, concentrations of VOAs and PAHs returned to near background levels by the end of May and have remained there since.

Oil sheens can occur from weathered crude oil washing off the shore. Oil sheens also are common in boat harbors and areas of heavy boat traffic and fishing. However, unlike these boat sheens which usually contain fuel oil, sheens of weathered crude oil have lost most of the toxic fractions of the oil and are much less toxic. Crude oil sheens were sampled in several heavily oiled bays of western Prince William Sound and found to contain only traces of potentially toxic PAHs. These sheens do not pose a hazard to water column organisms or to wildlife occupying the sea surface.

A comparison was made of the measured VOA and PAH concentrations in the water column and on the water surface (in sheens) of Prince William Sound with the published literature on the toxicity of petroleum to marine organisms, particularly Alaskan species. Average concentrations of petroleum hydrocarbons measured in more than 5,000 water column samples from Prince William Sound and the western Gulf of Alaska are well below (approximately 10 to more than 1,000 times below) concentrations that have been shown to

be toxic or cause harmful sublethal effects in marine animals.

It is extremely unlikely that hydrocarbon concentrations resulting from the spilled oil have had or will have any adverse effects on plants and animals living in the water column of Prince William Sound and the western Gulf of Alaska, including commercial fishery species.

WATER QUALITY IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

INTRODUCTION

Within a few days after the March 24, 1989, crude oil spill, Exxon initiated an extensive field sampling program to measure the concentrations and distribution of the spilled petroleum in the water column (the area between the ocean surface and above the sea floor) of Prince William Sound and the Gulf of Alaska. As part of this program, several private contract research laboratories (Arthur D. Little Marine Sciences Laboratory, Battelle Ocean Sciences Laboratory, America North Inc., Kinnetic Laboratories, Inc., and Dames and Moore) collaborated to collect and analyze water samples from many locations and water depths throughout this area. These samples were intended to provide a basis for an assessment of potential effects of the spilled oil on the marine plants and animals (including species important to the commercial and subsistence fisheries) of the Sound and the adjacent Gulf of Alaska. Water samples were collected periodically through the spring, summer, fall, and winter months of 1989 and 1990 at up to 35 offshore locations (generally more than one-quarter mile from shore) and at 65 nearshore locations (within a few hundred yards of shore) throughout Prince William Sound, particularly in areas through which the spilled oil moved. Additional water samples were collected at 95 offshore and nearshore locations in the northwestern Gulf of Alaska.

Results of the chemical analyses of these water samples indicate that the amounts of petroleum hydrocarbons per unit volume of seawater (concentrations) have remained very low from shortly after the spill through early March, 1990. The discussion that follows first describes the distribution and concentrations of petroleum hydrocarbons in offshore waters of Prince William Sound. Then it describes the distribution of hydrocarbons in nearshore waters of the Sound, particularly adjacent to heavily-oiled shores. Finally, it describes the distribution of petroleum hydrocarbons in offshore and coastal waters of the northwestern Gulf of Alaska.

After publication of the April, 1990 water quality report (Neff, 1990a), substantial additional water quality data became available. These data included the results of analysis of water samples from the February-March, 1990 Prince William Sound offshore water quality survey, additional analytical results from other offshore and nearshore surveys in Prince William Sound, and results of analysis of water quality samples from offshore and nearshore waters of the northwestern Gulf of Alaska in areas where some of the spilled oil moved. In addition, some of the raw data discussed in the April report were reprocessed to make methods consistent among analytical laboratories. This updated report includes a discussion of all the data, including the new and the reprocessed data.

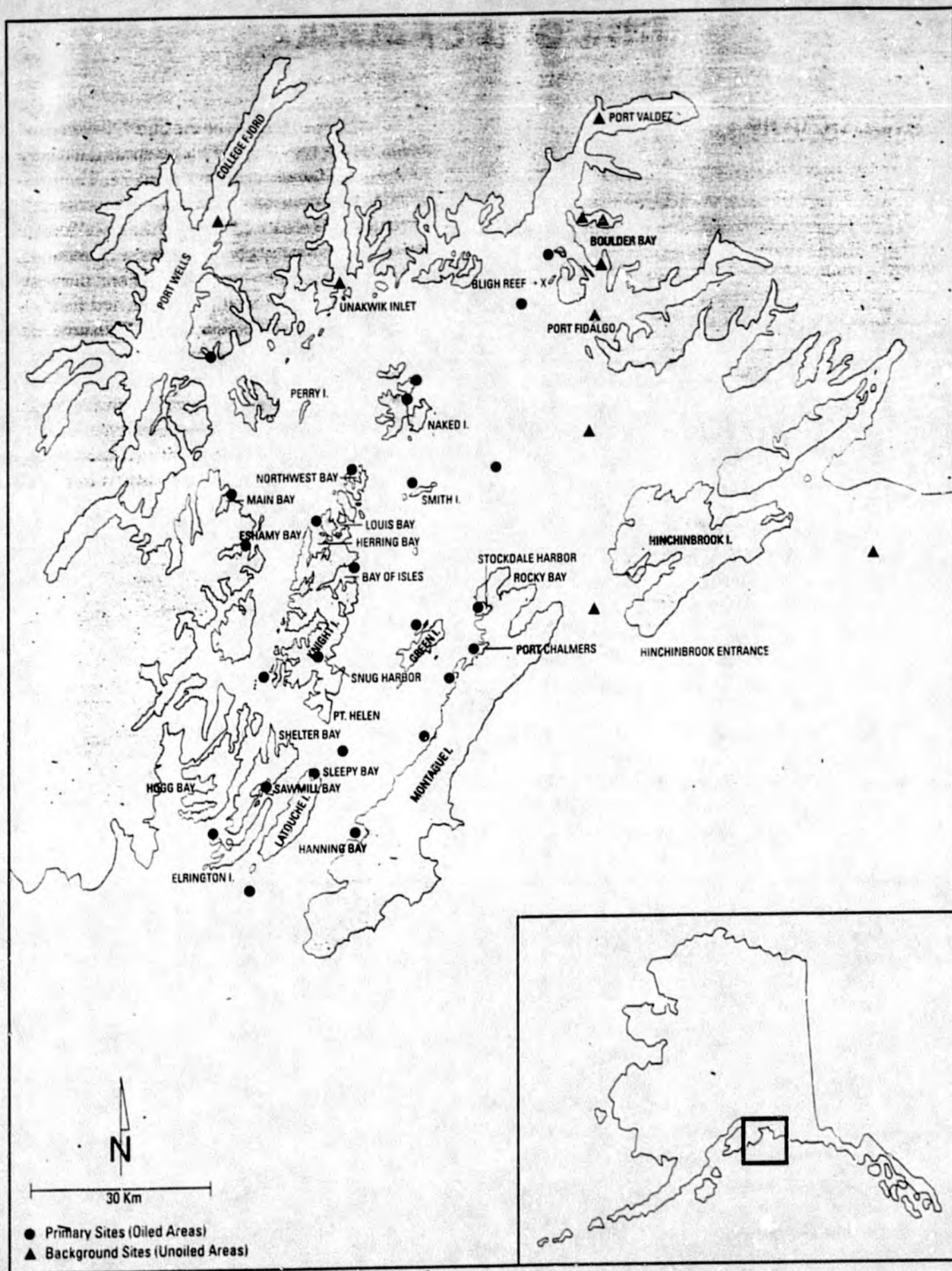


Figure 1. Station Locations in Prince William Sound Where Offshore Hydrocarbon Concentrations Were Measured.

WATER QUALITY IN PRINCE WILLIAM SOUND

OFFSHORE WATER QUALITY

FIELD PROGRAM

The first of Exxon's eight offshore water quality field surveys in Prince William Sound began on March 30, 1989. The most recent survey was completed in March, 1990. This section of the report contains a summary of the results of analysis of the 2,319 water samples (plus 845 quality control samples) collected in 1989 and early 1990 as part of the Prince William Sound offshore field surveys.

Sampling sites for the offshore water quality program were selected after discussions with state and federal agency personnel. A particular effort was made to identify and include areas important to wildlife and fisheries. About 40 percent of the sampling locations were in bays, and 60 percent were in more open waters of Prince William Sound. Several sampling sites also were selected in areas where the spilled oil did not go; these served as background or reference sites.

Sampling was performed at 35 stations (Figure 1), 29 of which were intended as primary sampling sites (locations where oil slicks or sheens had been reported or where oil was expected to drift). The other six stations were chosen in locations where it was apparent a few days after the spill that the oil would not go. These sites were designated as background or reference stations. Four of the original primary stations were located in areas where surface oil was never reported; thus, the offshore water quality program had 10 background and 25 primary stations. These are shown in Figure 1 as triangles and circles, respectively.

Water samples were collected from the water surface and from 1, 3, 9, and in some cases, 30 meters (approximately 3, 10, 30, and 98 feet, respectively) below the water surface, a depth interval believed to be sufficient to characterize oil contamination that might be present in the water column. From the third field survey onward, surface water samples were taken of any surface slicks that might be present in the general vicinity of a fixed sampling site. These samples were intended to represent the "worst-case" situation for oil contamination of surface waters of Prince William Sound.

Samples were collected, preserved, stored, and transported using well-established procedures. Rigorous quality assurance and quality control procedures were followed in all phases of the program, which included strict chain-of-custody procedures to ensure sample integrity from the time of collection through analysis in the laboratory and reporting of the final data. All samples from both primary and background stations were handled in the same way. Representatives of the Alaska Department of Environmental Conservation were included as observers on most of the water quality field surveys.

Quality control samples were collected during each field survey to ensure the reliability, accuracy, and precision of the sampling and analysis procedures. One sampling method was found to compromise sample integrity when quality control samples (called blanks) of high purity reference water that came in contact with the sampling device contained unreasonably high concentrations of some of the hydrocarbon classes. This sampling method was used to collect about 30 percent of the water samples from the first two field surveys; its use in the offshore Prince William Sound water quality study was discontinued after the second field survey. The results of some analyses of samples collected by this method are not included in this report, as discussed further in the Appendix.

PETROLEUM HYDROCARBON ANALYSIS

During the last 20 years, methods for the analysis of petroleum hydrocarbons in seawater have improved substantially. The methods used in Exxon's water quality program are either the latest EPA-approved methods or modifications of approved methods intended to increase the sensitivity of the analysis so that even very low concentrations of petroleum hydrocarbons can be detected and quantified. These sensitive and accurate methods are also able to distinguish between hydrocarbons from the spilled crude oil and those from other sources (e.g., diesel fuel, engine exhaust, or natural biological hydrocarbons).

Crude oil is a complex mixture of thousands of organic compounds of fossil biological origin. Most of these compounds are hydrocarbons (organic

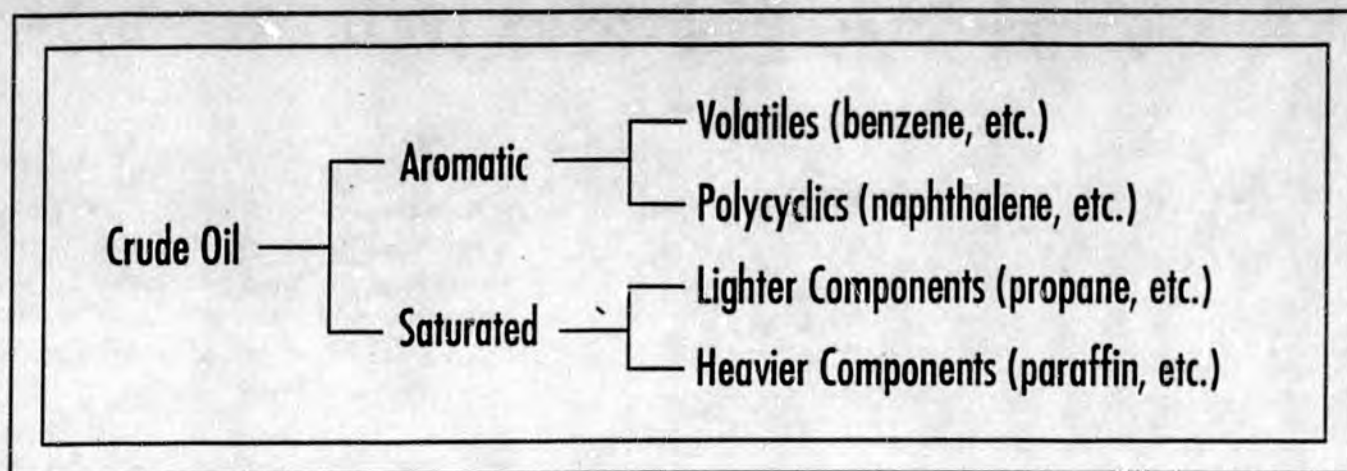


Figure 2. Crude Oil Hydrocarbon Groups

compounds made up of only carbon and hydrogen). There are two main groups of hydrocarbons: saturated and aromatic (Figure 2). In both groups, individual compounds range from low molecular weight, very volatile compounds such as propane (saturated) and benzene (aromatic) to high molecular weight, less volatile compounds like paraffin (heavy saturates) and naphthalene (polycyclic aromatic hydrocarbons).

Although crude oils may contain large amounts of volatile hydrocarbons, these volatile components evaporate so quickly from spilled oil on the water surface that they rarely cause adverse biological effects in water column plants and animals. Some of the medium-size polycyclic aromatic hydrocarbons (such as naphthalene) are slightly soluble and cause most of the toxicity of crude oil to marine organisms after a spill (Neff, 1990b). These compounds gradually disappear from the spilled oil through weathering (e.g., evaporation into the atmosphere, dissolution into and rapid dilution in the water column, microbial degradation, and degradation by sunlight). Some of the products of microbial and photodegradation of petroleum hydrocarbons are quite soluble and toxic. However, scientists at the National Marine Fisheries Service have shown that these degradation products are produced slowly and lost so rapidly through dissolution and dilution that they do not increase the toxicity of weathering oil (Malins et al., 1983). Thus, the toxicity of oil decreases continuously with time after a spill.

The concentrations in the water column of petroleum hydrocarbons resulting from oil spills usually are very low and it is difficult to visualize what the reported concentrations mean. A con-

centration of 1 part per million (ppm) is approximately equivalent to one cup of oil mixed uniformly in 50,000 gallons of water. Similarly, 1 part per billion (ppb) and 1 part per trillion (ppt) are equivalent to one cup of oil dissolved in 50,000,000 and 50,000,000,000 gallons of water, respectively. These volumes correspond to cubes approximately 19, 190, and 1,900 feet on a side.

ANALYTICAL RESULTS

Four types of analyses were performed on water samples collected for this study. Each type of analysis measures a different group of hydrocarbons and has a different sensitivity and ability to distinguish between petroleum hydrocarbons and organic compounds from other sources, as described below.

• Volatile Organic Analytes (VOA)

The VOA analysis is specific for measuring the concentrations of the low molecular weight, volatile aromatic hydrocarbons such as benzene, toluene, and xylene. Although these compounds are abundant in petroleum, there are many other sources of VOAs in the environment. (The concentration of benzene in the atmosphere, including remote regions of the globe, ranges from 0.1 to 14 ppb: Fishbein, 1984. Atmospheric benzene and other VOAs are derived from evaporation of petroleum products, industrial emissions, burning of wood and other organic materials, and natural decay of organic matter: Fishbein, 1984, 1985 a,b,c. VOAs may enter the ocean, even in remote areas, in rainfall.) These volatile aromatic hydrocarbons evaporate very rapidly from the water surface and from the upper water column.

(The half-life of benzene in water is about 37 minutes: Fishbein, 1984.)

When detected at all in the water column, VOAs are present nearly always at very low concentrations. The detection limit for the VOA analytical method is about 1 ppb. Many of the results obtained in this study were below this method detection limit. Thus, average concentrations for groups of samples from a field survey often were below 1 ppb because the averages included zero values. (For completeness, additional detail concerning sample data and numerical treatment of concentrations below the detection limits are provided in the Appendix.)

The highest measured concentrations of volatile aromatic hydrocarbons in the water column occurred in the days immediately after the spill (Figure 3). The curve in Figure 3 was constructed from the average concentrations of VOAs from all depths at all primary stations for each field survey. VOAs were not measured in the February-March, 1990 survey. The average measured concentration of VOAs peaked at slightly less than 2 ppb at the time of the second field survey in early April (April

4 to 10). The lower average VOA concentration at the time of the first water quality field survey may be because the spilled oil had not yet reached all the primary stations at the time of that field survey. In addition, because of contamination problems with one of the sampling devices (discussed above), results of analysis of many subsurface water samples from the first field survey were rejected.

At the time of the first and second field surveys in late March and early April, the average concentration of VOAs in the water column at background sites was about 1 ppb, comparable to average concentrations in field blank samples collected at the same times. By late April, the average concentrations of VOAs at background (0.18 ppb) and primary (0.20 ppb) sites were indistinguishable, and comparable to concentrations in blank samples, and they have not varied significantly since then. The decrease in VOA levels in background and blank samples from 1 ppb to about 0.18 ppb was due primarily to improvements in the sampling and analytical methods that resulted in lowering in the limits of detection for the analytical technique.

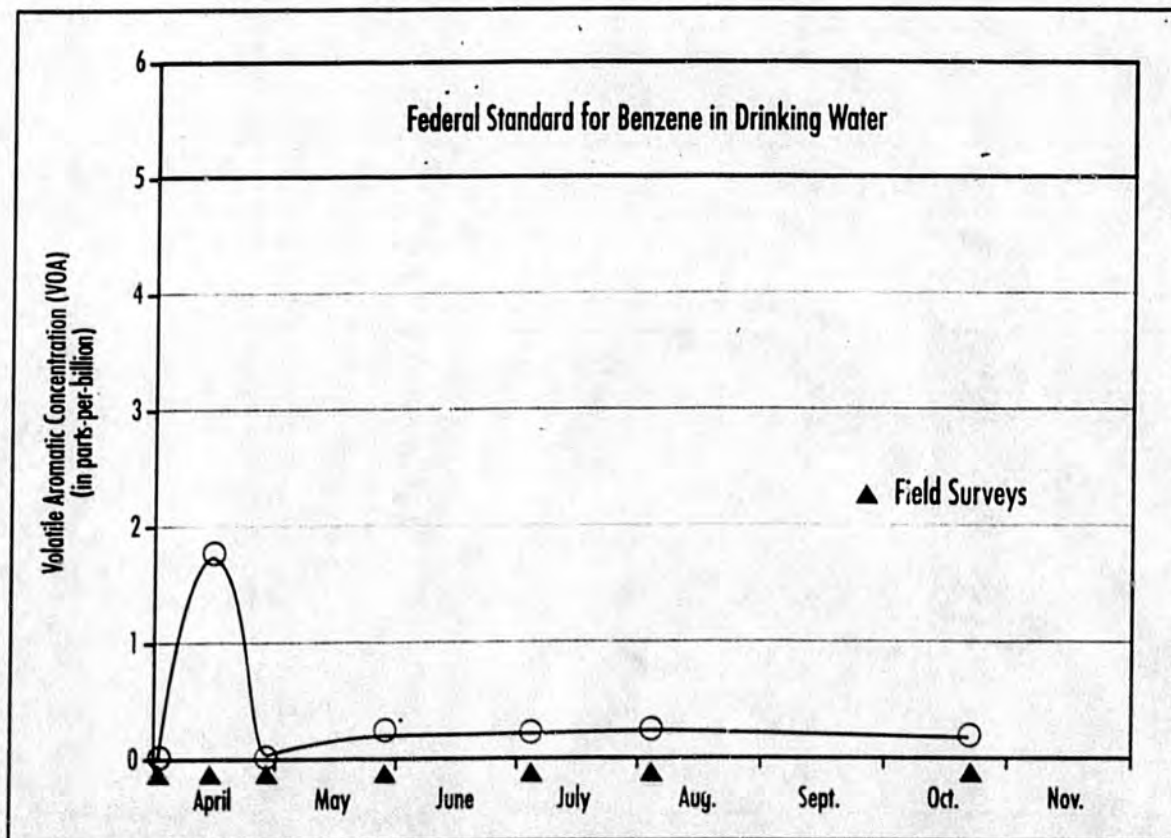


Figure 3. Average Volatile Aromatic (VOA) Concentrations at Primary Offshore Sites in Prince William Sound

When quality control samples (blanks) yield concentrations similar to those in seawater samples, it is an indication that the analysis method is being pushed to its limit of applicability. In such cases, actual concentrations in the water column probably are lower than the values reported.

To put these extremely low concentrations in perspective, the federal standard for the concentration of benzene (one of the components of VOA) in drinking water is 5 ppb, a benzene concentration never exceeded in any seawater sample collected with noncontaminating water sampling devices during the offshore water quality program in Prince William Sound.

A total of 755 water samples (including 302 quality control samples) were collected for VOA analysis. Of the 453 samples of seawater from Prince William Sound, more than 91 percent (413 samples) contained less than 1 ppb total VOAs (Figure 4). Only 1.5 percent of samples (seven samples collected from primary stations in April) contained more than 5 ppb total VOAs. The highest concentration measured was 25 ppb.

As described above and in the Appendix, one water sampling device was difficult to clean to the required standards and VOA data from samples collected with that device were not used. Another sampling device used also had contamination problems, but not severe enough to warrant

rejection of the data produced for samples collected with it. This sampler was used almost exclusively to collect water samples from 3 and 9 meters below the water surface. All 7 of the water samples containing more than 5 ppb VOA were collected with this sampler during the second water quality survey (early April) from 3 or 9 meters below the water surface, and probably were contaminated by the sampling device.

Given the generally very low concentrations of VOAs at all stations and the short duration of slightly elevated concentrations of VOAs in the water column at a few primary stations in April, it is extremely unlikely that any adverse effects to water column organisms in Prince William Sound occurred as a result of exposure to these volatile aromatic hydrocarbons.

• Polycyclic Aromatic Hydrocarbons (PAH)

Polycyclic aromatic hydrocarbons are composed of two or more fused (sharing two carbon atoms) benzene rings. Most PAH in the marine environment come from two sources, petroleum products and soot produced by the burning of organic materials, including fuels (Neff, 1979). More than 90 percent of the PAH in crude oil contain two or three rings. These compounds are slightly soluble in seawater (solubility of naphthalene is about 22 ppm and that of phenanthrene is about 1 ppm) and they are moderately toxic to marine organisms (Neff and Anderson, 1981). Because they evaporate from seawater more slowly than the VOAs, they are thought to be the most important contributors to the toxicity of spilled oil to organisms living in the water column (Neff, 1990b).

PAHs do not persist long in solution in the ocean. They adsorb rapidly to solid surfaces, such as particles suspended in the water, or collect at the water surface to form a surface sheen. Because the concentrations of these compounds in the water column are so low, the detection capabilities of an existing EPA-approved analytical method were improved by a factor of about 100 to allow better tracking of the distribution and fate of these components of oil in the water column over time. The method developed has a nominal detection limit of about 10 parts per trillion (0.01 ppb) per component (e.g., naphthalene) of the PAH mixture. However, during the course of the Prince William Sound and Gulf of Alaska water quality programs, the method was modified to lower the

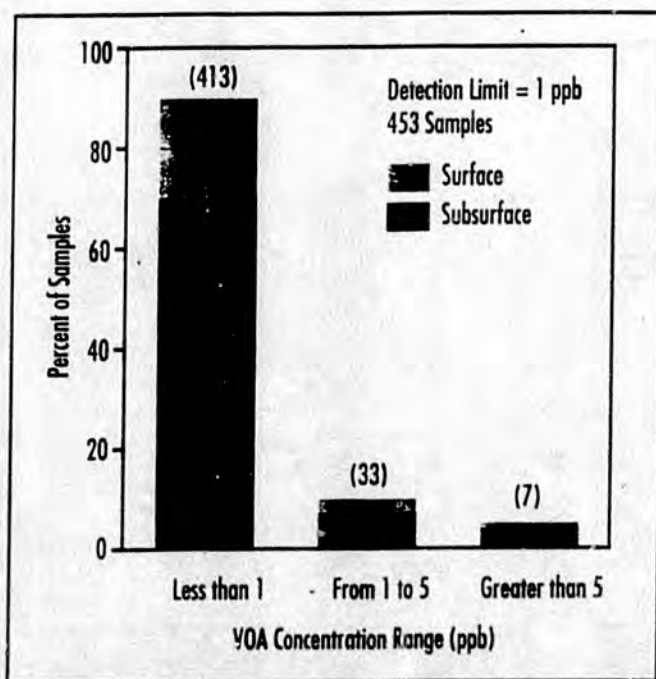


Figure 4. Distribution of Volatile Organic Analyses (VOA) (Offshore Prince William Sound)

detection limits even further. The method was also modified to improve its specificity for PAHs characteristic of crude oil. Total PAH, as discussed in this report, is the sum of the concentrations of a total of 37 individual PAHs ranging from naphthalene to benzo[ghi]perylene.

A total of 1,003 water samples for PAH analysis were collected between the end of March, 1989 and March, 1990 as part of the offshore water quality program. This total includes 203 samples collected for quality control. As with the VOA concentrations, average concentrations of PAHs in the water column of Prince William Sound reached a peak in April (Figures 5a and 5b). As expected, the highest concentrations were in bays and offshore waters near islands in the western Sound where large amounts of oil drifted in the first few weeks after the spill. The highest average concentration of total PAH in the water column of the three most heavily contaminated sites in the period shortly after the spill (Bay of Isles, Smith Island, and Herring Bay) was only 0.7 ppb (7 percent of the State of Alaska marine water quality standard of 10 ppb aromatic hydrocarbons: Figure 5b). The slightly elevated average value (0.32 ppb) indicated on the July survey results almost entirely from a single surface sample with a 3.2 ppb PAH concentration from Smith Island. The inclusion of this sample analysis increased the average value from 0.041 ppb to the 0.32 ppb indicated in Figure 5a. The highest average concentration of total PAH at all primary sites was about 0.2 ppb, only 1/50th of the State standard. This average value was recorded for samples collected during the third field survey about 1 month after the spill.

As expected, the average concentrations of total PAH in seawater from background sites were very low (the highest mean value was 0.08 ppb) and did not vary significantly with time during the spring and summer of 1989. The apparent very slight elevation in the average concentration of total PAH in seawater from background sites at the time of the second and third field surveys in April was due to four samples (two from each survey) containing much higher concentrations of total PAH than other samples from all background sites.

The two anomalous samples from the second field survey were collected from 1 and 9 meters at an open-water site about halfway between Port Fidalgo and the north shore of Hinchinbrook Island just east of the tanker lanes. The anomalous

samples from the third field survey were collected from 3 meters at Unakwik Inlet and from the surface in upper College Fjord. The College Fjord sample had the highest concentration of total PAH (0.99 ppb: one-tenth of the Alaska standard) of all water samples from background sites and may have been contaminated by a micro-tarball or bilge washings from the survey vessel. The PAH assemblage had characteristics of both a diesel fuel and a pyrogenic (engine exhaust) source.

The average concentrations of total PAH in water samples from the fourth through eighth field survey ranged from 0.02 to 0.06 ppb. Thus, the results of the analysis of water samples from background sites both north and east of where the spilled oil drifted provide strong evidence that there was not widespread contamination of the water column throughout Prince William Sound, even for a short period after the spill.

However, elevated concentrations of PAH were observed at some primary sites, particularly during April. Between March and June, 1989, the highest average concentrations of total PAH at primary sites occurred in samples from the water surface (Figure 6a). PAH concentrations tended to decrease with depth in the water column. Samples collected from the water surface following an oil spill often contain sheen, mousse, or tar balls that were floating on the water surface and so were not actually present in the water column. The average concentration of total PAH in water samples from the surface reached a peak of nearly 0.9 ppb in late April. The highest average concentration of total PAH in deeper waters (1, 3, 9, and 30 meters) was just over 0.1 ppb and was reached in mid-April. After the fifth field survey (early July), average PAH concentrations were uniformly low (mean concentrations ranging from 0.03 to 0.06 ppb) at all water depths. These concentrations were similar to those in water samples from background stations and in blanks collected at the same time as the water samples. Therefore, they reflect a return to background conditions in the offshore water column of Prince William Sound. All average concentrations are well below the Alaska standard (Figure 6b).

As shown in Figure 7, 6.5 percent of all water column samples (52 of 798 samples) from the offshore water quality program contained total PAH concentrations below the approximate method detection limit of 0.01 ppb (10 parts per trillion). More than 78 percent of the samples

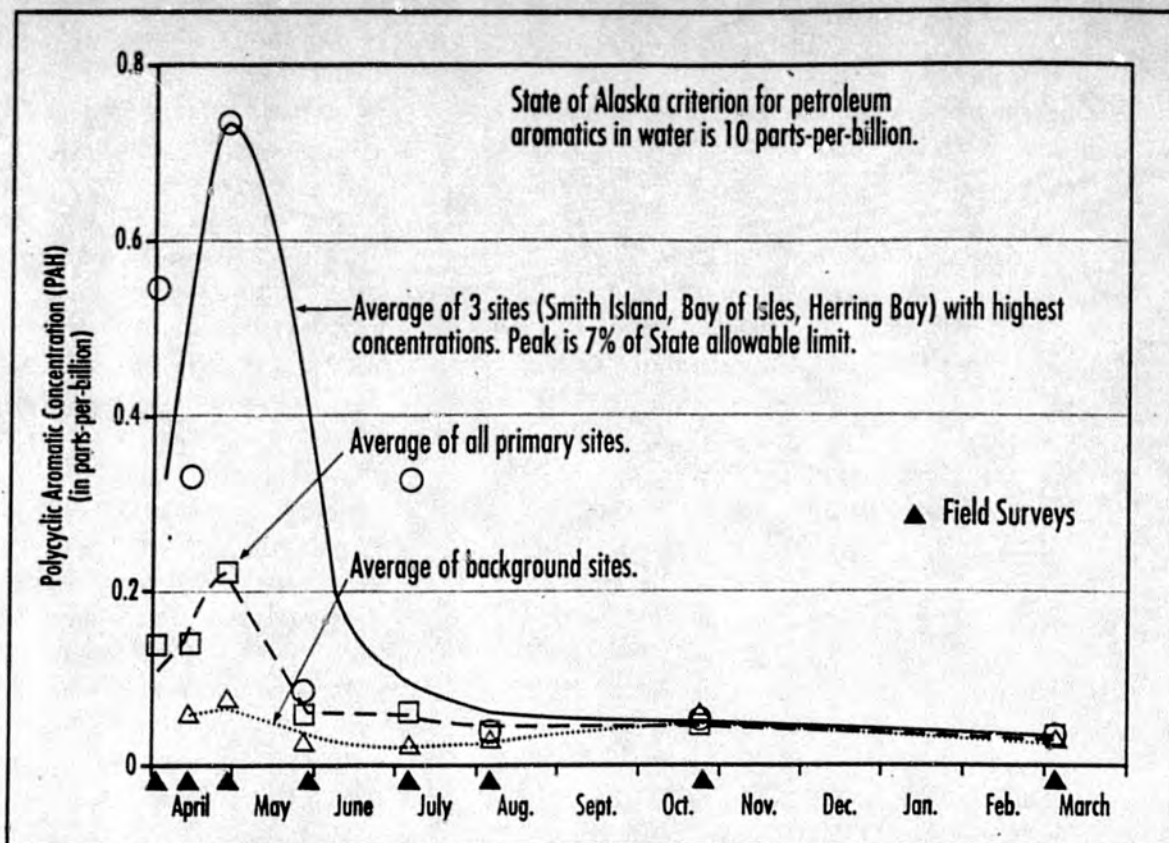


Figure 5a. Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations at Primary Offshore Sites in Prince William Sound

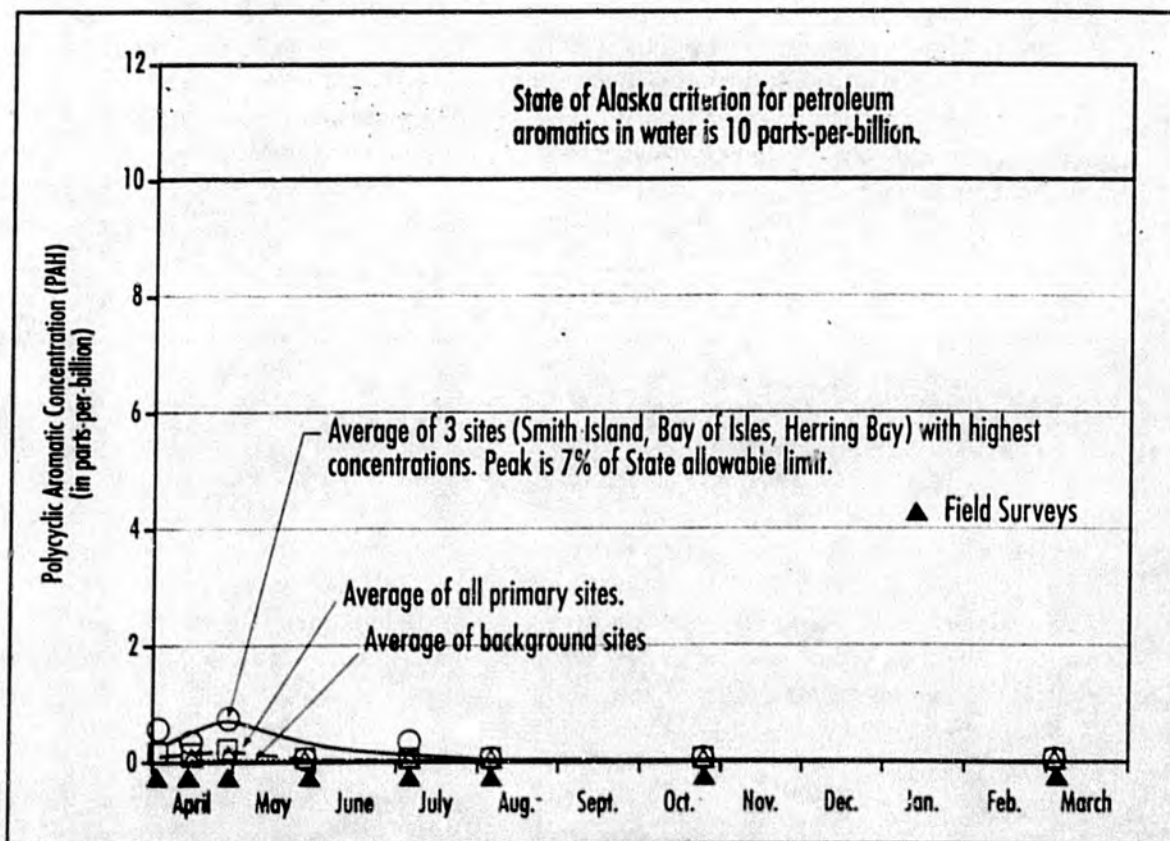


Figure 5b. Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations at Primary Offshore Sites in Prince William Sound (expanded scale)

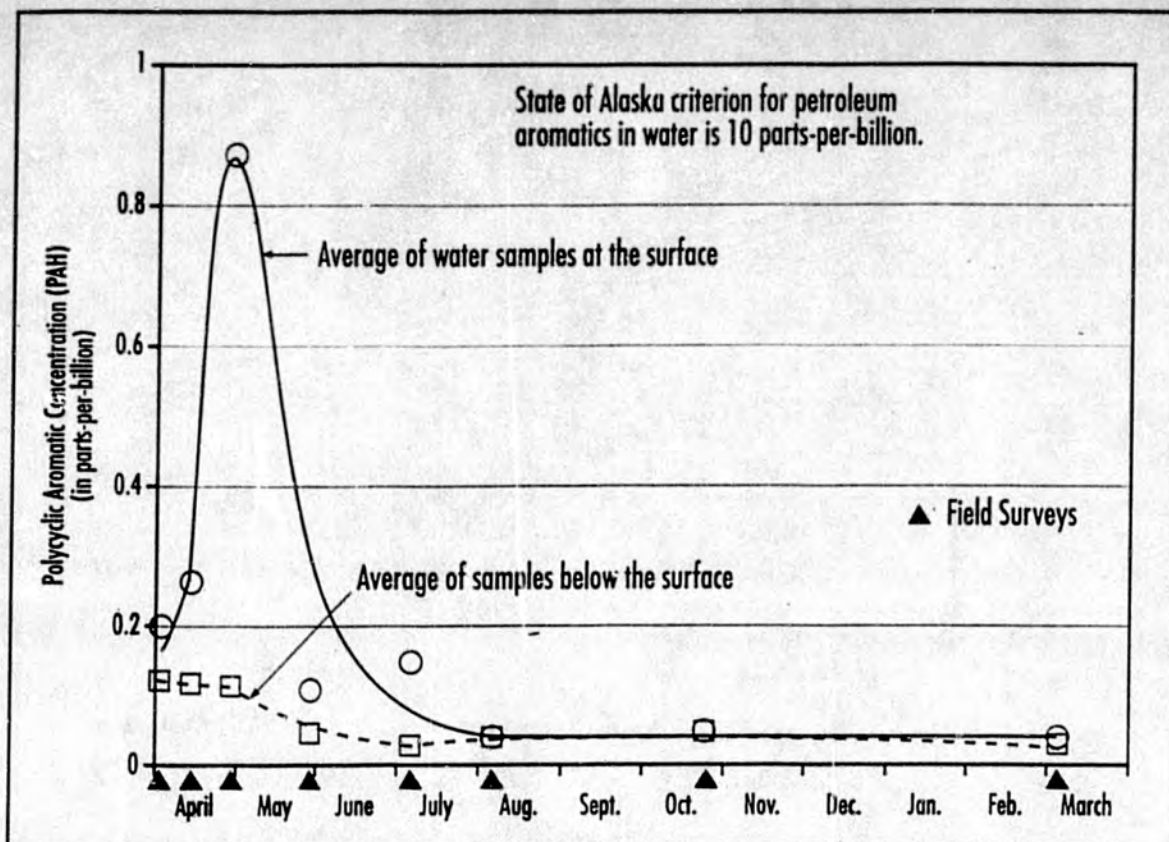


Figure 6a. Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations for Surface and Deeper Water at Primary Offshore Sites in Prince William Sound

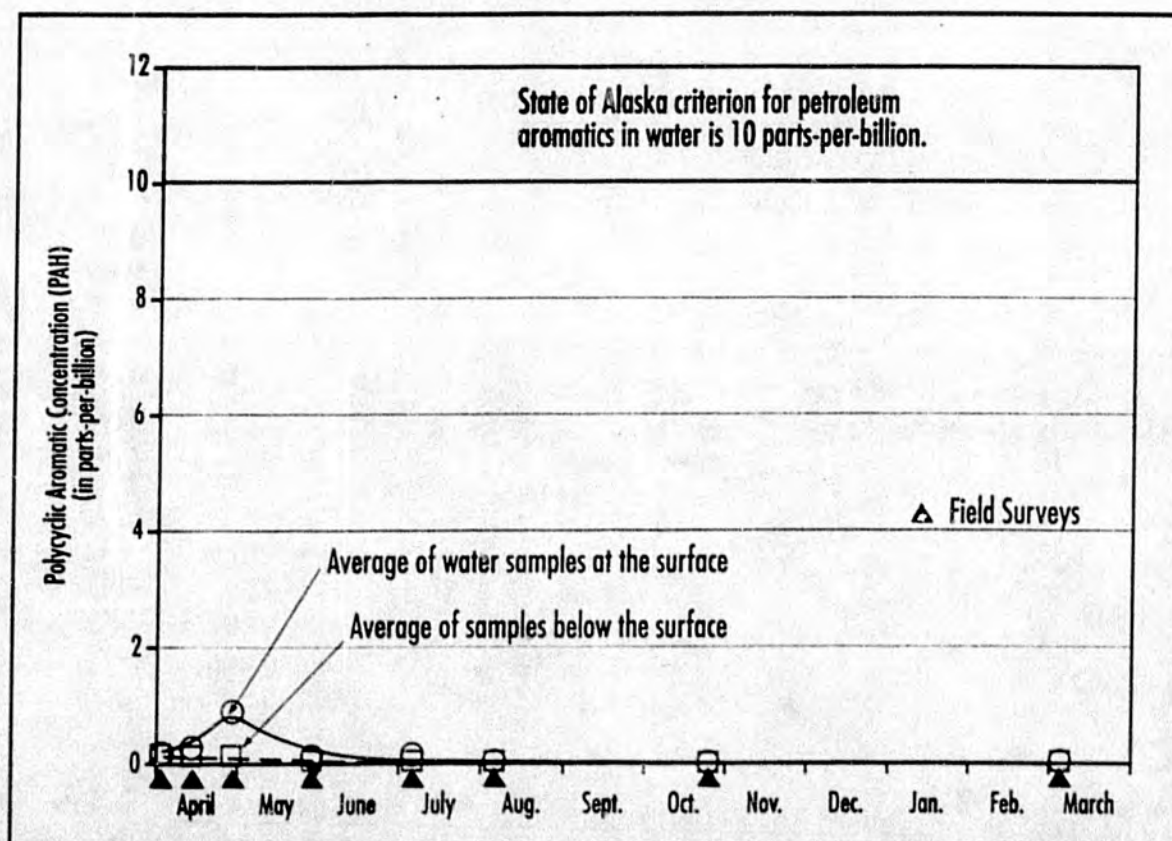


Figure 6b. Average Polycyclic Aromatic Hydrocarbon (PAH) Concentrations for Surface and Deeper Water at Primary Offshore Sites in Prince William Sound (expanded scale)

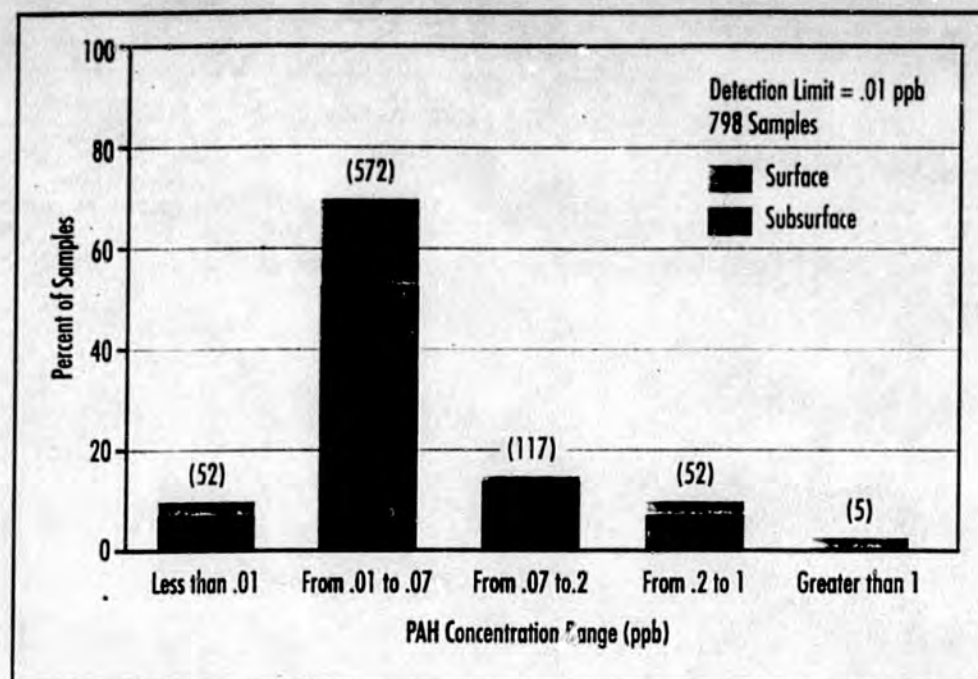


Figure 7. Distribution of Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Offshore Prince William Sound)

contained 0.07 ppb or less of total PAH. One surface water sample each from Snug Harbor and Northwest Bay, collected in late April, contained 12.5 and 41.7 ppb PAH, respectively. These samples contained mousse material [see the discussion of total petroleum hydrocarbon (TPH) concentrations below] and so were not included among the samples used to calculate means. The next highest PAH concentration measured in a sample collected in this program was 7 ppb. This sample was from the surface and was collected in late April from the Bay of Isles, a heavily oiled area. Only 5 water samples (0.6 percent) contained more than 1 ppb PAH. All these samples were surface water samples.

The highest average concentrations of total PAH shown in Figures 5, 6, and 7 are at least 10 to 1,000 times lower than concentrations that are lethal or cause harmful sublethal effects in even the most sensitive species and life stages of marine organisms. In addition, the distribution of PAH in the water column has been extremely uneven over both wide temporal and spatial scales so that organisms occupying different positions in the water column probably would not be exposed for long to any PAH concentrations higher than background levels.

• **Petroleum Hydrocarbons (PHC) and Total Petroleum Hydrocarbons (TPH)**

Two additional methods were used to characterize the distributions and concentrations of petroleum hydrocarbons in the water column. The first of these methods is a gas chromatographic analysis of total recoverable petroleum hydrocarbons (PHC). It has a detection limit of about 50 ppb and measures all the petroleum hydrocarbons (both saturated and aromatic) in the sample. It is subject to interference by saturated hydrocarbons produced naturally by terrestrial plants and marine plants and animals.

The second method is an infrared analysis for total hydrocarbons (TPH). It is not very sensitive (detection limit of about 1 ppm), is very subject to interference from nonpetroleum organic matter, and is useful only for rapid screening at heavily contaminated sites. These two methods are used primarily to provide estimates of the concentration of total petroleum hydrocarbons in samples. In addition, gas chromatographic analysis provides information on the composition and relative concentrations of saturated hydrocarbons in the sample. This information may be used with the PAH compositional information to identify the source of the hydrocarbons present in a sample.

More than 89 percent of the water samples analyzed for PHC contained nondetectable concentrations (less than 50 ppb); slightly less than 3 percent (23 of 778 water samples) contained more than 100 ppb, and the remainder contained from 50 to 100 ppb. The highest values obtained corresponded to the highest values for PAH, mentioned above. All of these were surface samples from Snug Harbor (459 ppm PHC), Northwest Bay (1,700 ppm PHC), and the Bay of Isles (1 ppm PHC). The first two concentrations are much larger than the solubility of hydrocarbons in sea water and contained mousse material, as confirmed by the contractor involved. The Bay of Isles sample may have contained some sheen oil, as the PAH profile in the sample resembled that of weathered North Slope crude oil.

Concentrations of TPH in more than 96 percent of all seawater samples (276 of 286 samples) were below the method detection limit. Additional information about the results of PHC and TPH analyses, including figures, is provided in the Appendix.

OFFSHORE RESULTS SUMMARY

More than 3,160 samples of water (including 845 quality control samples) collected at offshore locations throughout Prince William Sound and at several water depths between the end of March, 1989 (6 days after the spill) and March, 1990 have revealed that the concentrations of total petroleum hydrocarbons as well as the toxicologically more important volatile aromatics (VOAs) and polycyclic aromatic hydrocarbons (PAH) have been consistently very low. Highest concentrations occurred in April, within one month of the spill, and then quickly returned to near background levels where they have remained ever since. The highest concentrations of PAH that were observed always occurred in samples from the water surface and probably contained sheen, mousse, or tar ball material.

NEARSHORE WATER QUALITY

A total of 1,342 water samples (plus 690 quality control samples) were collected for analysis of petroleum hydrocarbons in shallow waters adjacent to oil-contaminated shores in Prince William Sound. Study sites were selected to encompass a wide variety of shoreline types, extent of exposure to the energy of storm waves, and

degrees of oil cover. Two types of study sites were included in the nearshore water quality program:

- **Shoreline Monitoring Sites**

At these 51 oiled sites, nearshore water quality was monitored five times between March and October, 1989, independent of the time the sites were treated. These sites are identified by circles in Figure 8.

- **Shoreline Treatment Monitoring Sites**

At 14 sites, water quality samples were collected outside boomed areas before and at intervals between 1 and 30 days after treatment of the adjacent shoreline by different methods to remove oil. These sites are identified by triangles in Figure 8.

FIELD PROGRAM

Water samples were collected at shoreline monitoring sites during five field surveys from March through October, 1989. Water samples were collected below the low tide line at or near the water surface and at depths below the surface ranging from 1 to 42 meters (3 to 138 feet).

Water samples were collected between mid-July and mid-September, 1989 at shoreline treatment monitoring sites in western Prince William Sound shortly before (usually one day) and at intervals between 1 and 30 days after the adjacent shoreline was treated with cold water, high-pressure hot water, beach cleaning agents, or a combination of methods to remove oil. During treatment, oil from the shore was washed onto the nearshore water surface in an area enclosed by booms. The oil on the water surface was recovered with skimming equipment. Water samples were collected outside boomed areas 0.5 to 1 meter (1.5 to 3 feet) below the surface and 0.5 meter (1.5 feet) above the bottom at locations offshore near where the booms were deployed.

Sampling methods, sample-handling procedures, quality assurance/quality control, and analytical methods were the same as used for the offshore water quality program.

ANALYTICAL RESULTS

The focus of the discussion here is on the potentially toxic VOAs and PAHs in the water column adjacent to oiled shores. As with the water samples from the offshore water quality program, most measurements of PHC (82 percent) and TPH

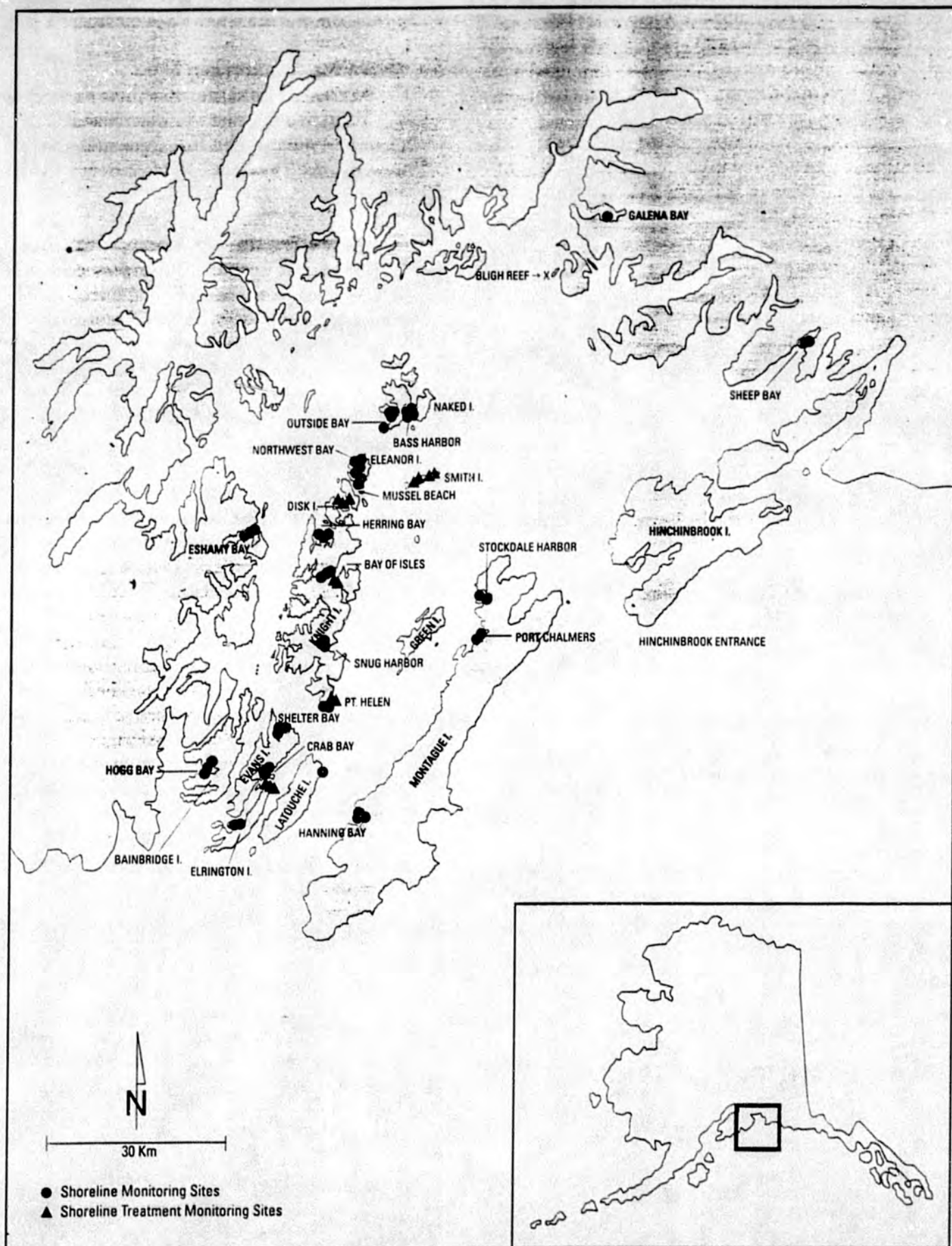


Figure 8. Station Locations in Prince William Sound Where Nearshore Hydrocarbon Concentrations Were Measured.

(96 percent) were below the method detection limits, indicating that concentrations of total petroleum hydrocarbons were generally very low in the water column adjacent to oiled shores. The results of these analyses are discussed further in the Appendix.

• **Volatile Organic Analytes (VOA)**

The results of the analysis of 349 water samples from shoreline monitoring sites for VOAs (plus 194 quality control samples) are shown in Figure 9. No samples for VOA analysis were collected during the shoreline treatment monitoring study. Concentrations of VOAs in 82 percent of the water samples (286 samples) were below the method detection limit of about 1 ppb; 16 percent contained between 1 and 5 ppb, and 1.7 percent (6 samples) contained more than 5 ppb.

The highest VOA concentration measured was 16 ppb in a surface water sample collected in Northwest Bay on Eleanor Island on June 24. The water sample from the 1-meter depth at the same sampling station and date contained 12.7 ppb total VOAs. Other water samples from several depths and locations in Northwest Bay sampled on the same date contained from 1.7 to 6.3 ppb total VOAs, indicating that the distribution of VOAs in the water column of the bay was very uneven. Most of the volatile aromatics in these samples were toluene and xylenes. Concentrations of benzene were below the federal standard for drinking water. It is highly probable that the concentrations of VOAs in even the most heavily contaminated samples were many times lower than concentrations that might cause adverse effects in sensitive marine organisms.

• **Polycyclic Aromatic Hydrocarbons (PAH)**

Results of the analysis for PAH of 310 water samples (plus 158 quality control samples) collected during the shoreline monitoring program are summarized in Figure 9. As described below, one sample, that apparently included a tar ball, was excluded from Figure 9. Results are also included from the analysis of an additional 82 water samples (plus 55 quality control samples) collected during the shoreline treatment monitoring program.

Most of the shoreline monitoring samples for PAH analysis were collected during the June-July and September-October field surveys. The shoreline treatment monitoring study samples were collected between mid-July and mid-September.

Concentrations of total PAH in about 11 percent (42 samples) of the water samples from both studies combined were below the method detection limit of about 0.01 ppb. Over 73 percent of the water samples contained from 0.01 to 0.2 ppb total PAH, and 12 percent (47 samples) contained between 0.2 and 1 ppb total PAH. A total of 16 samples (4 percent) from both studies contained more than 1 ppb total PAH.

Eight of the 16 samples that contained more than 1 ppb total PAH were obtained in the shoreline monitoring study on June 24 from Northwest Bay, the site and time of the collection of the water samples containing high VOA concentrations.

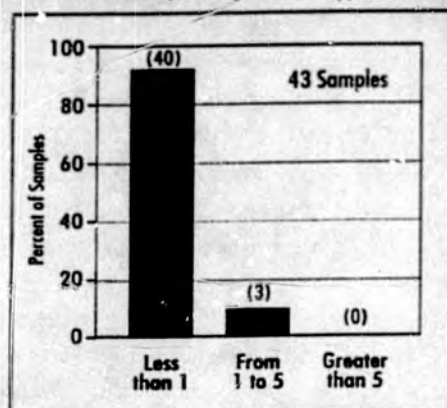
The sample with the highest concentration (30 ppb total PAH) was a surface water sample from the same location in Northwest Bay as the surface sample containing the highest concentration of VOAs. Water samples from other locations and water depths in Northwest Bay sampled in June contained between 0.39 and 14 ppb total PAH, indicating, as did the VOAs, a very uneven distribution of hydrocarbons in the water column of the bay. Water samples collected from Northwest Bay during the next field survey in September contained between 0.005 and 0.014 ppb total PAH, suggesting that the presence of elevated concentrations of PAH in the water column of this bay was a short-lived event. One water sample from 1 meter below the water surface, collected off a heavily oiled beach at the entrance to Shelter Bay in mid-September as part of the shoreline monitoring study, contained 710 ppb total PAH and apparently contained a tar ball. This sample was excluded from consideration. Eight other samples collected at the same time and location from several water depths contained between 0.01 and 0.04 ppb PAH.

Five water samples from the shoreline treatment monitoring study contained more than 1 ppb total PAH. Three of the samples were from the water surface and two were from one meter below the surface; the samples contained 1.0 to 2.4 ppb PAH and were collected after treatment of heavily oiled beaches on Disk and Knight Islands.

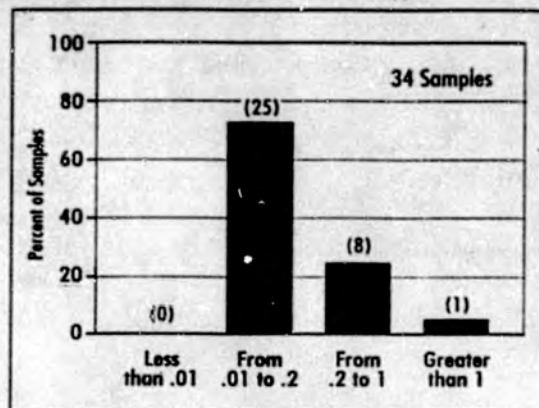
Shoreline Monitoring Sites

March - May
Surveys

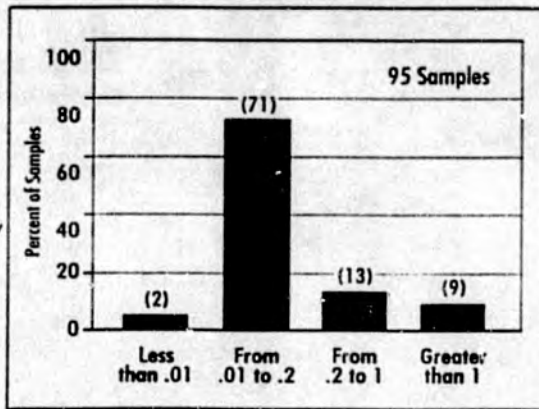
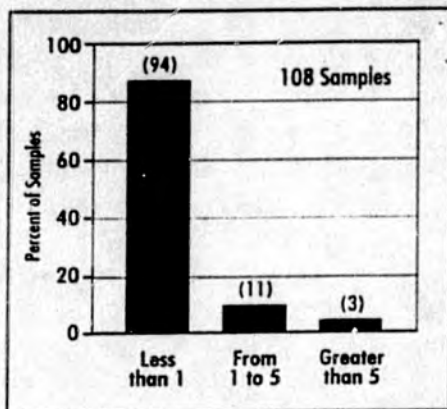
VOA (Detection Limit = 1 ppb)



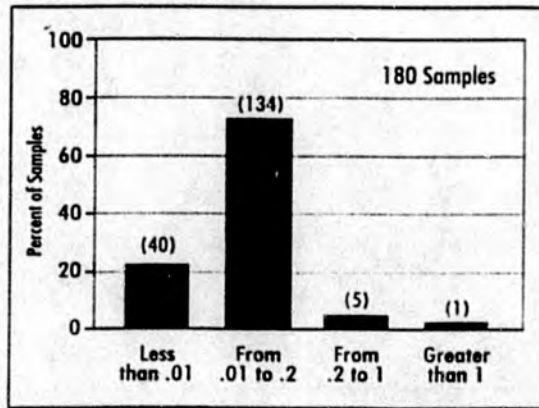
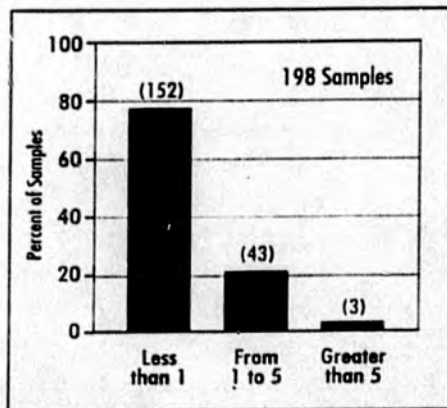
PAH (Detection Limit = .01 ppb)



June - July
Surveys



September -
October
Survey

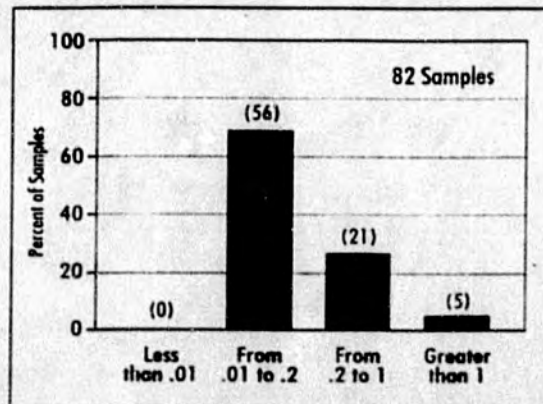


VOA Concentration Range (ppb)

Shoreline Treatment Monitoring Sites

July -
September
Surveys

No VOA Measurements
Made at Shoreline Treatment Sites



PAH Concentration Range (ppb)

Figure 9. Distributions of Volatile Aromatic (VOA) and Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Nearshore Prince William Sound)

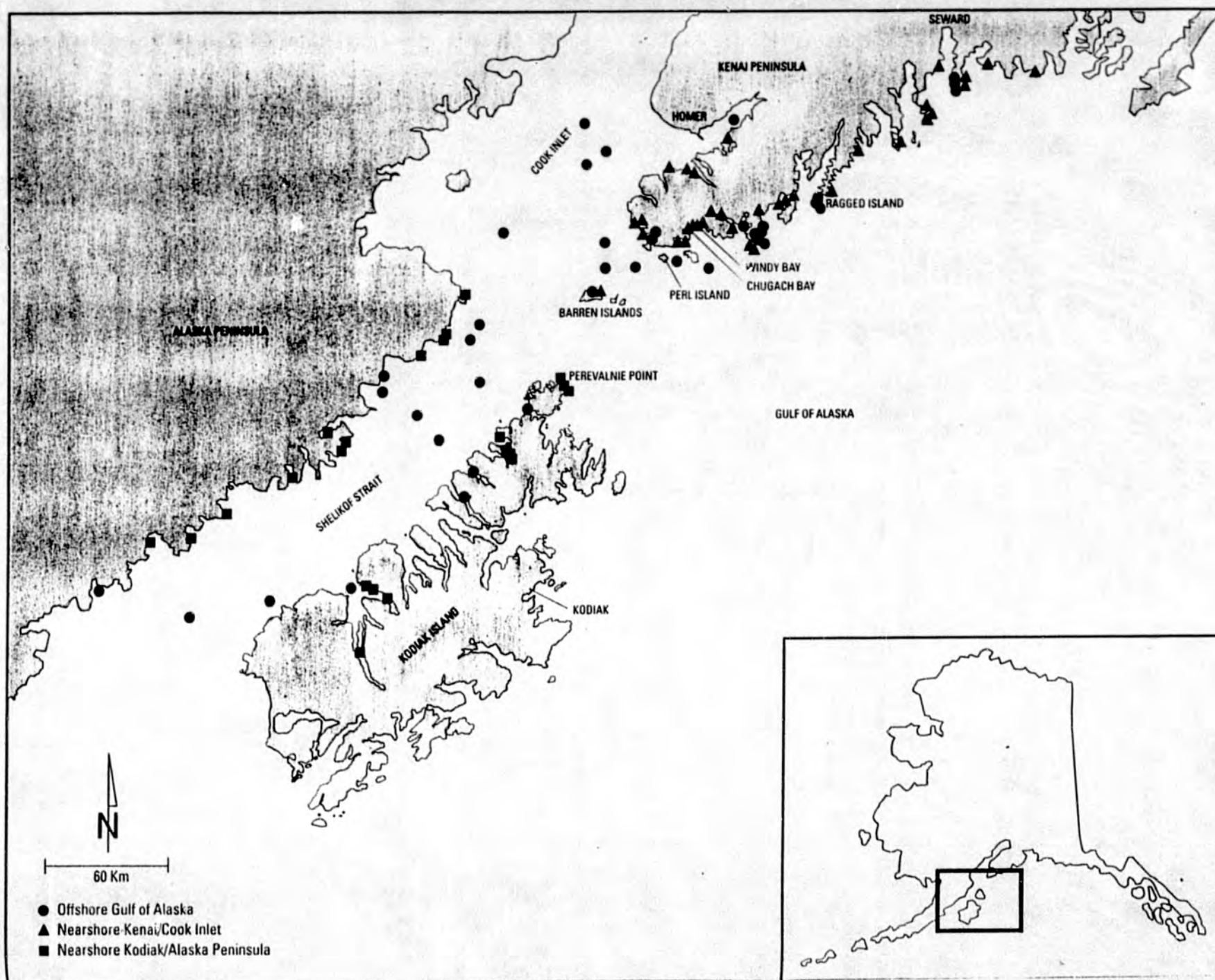
NEARSHORE RESULTS SUMMARY

Water samples collected near several oiled shorelines in Prince William Sound contained very low concentrations of VOAs and PAHs, comparable to those measured in water samples collected during the offshore water quality program.

Therefore, it is highly unlikely that petroleum hydrocarbons present at trace concentrations in the water column adjacent to oiled shores produced any adverse effects on marine plants and animals living in the water column.

The highest concentrations were localized in sheltered bays (particularly Northwest Bay, a heavily oiled site). Even in these sheltered bays, concentrations of petroleum hydrocarbons in the water column were quite variable in both space and time, strongly suggesting that these elevated concentrations were short-lived.

Figure 10. Station Locations in Western Gulf of Alaska Where Hydrocarbon Concentrations Were Measured.



WATER QUALITY IN THE GULF OF ALASKA

A total of 1,356 water samples (plus 870 quality control samples) were collected for analysis of petroleum hydrocarbons from coastal and offshore areas of the western Gulf of Alaska (Figure 10) where some of the spilled oil moved. Three water quality studies were performed in the Gulf of Alaska:

- **Gulf of Alaska Offshore Water Quality Study**

Water samples were collected at 39 locations in offshore waters of the western Gulf of Alaska and lower Cook Inlet in April and May, 1989. Samples were collected in areas through which oil slicks and mousse were moving.

- **Kenai/Cook Inlet Nearshore Water Quality Study**

Water samples were collected in nearshore waters adjacent to 34 oiled shorelines during April and August of 1989.

- **Kodiak/Alaskan Peninsula Nearshore Water Quality Study**

Water samples were collected in nearshore waters adjacent to 22 oiled shorelines during July and August of 1989.

FIELD PROGRAM

Samples were collected during four field surveys during April and May, 1989 as part of the Gulf of Alaska Offshore Water Quality Study. Each field survey was to a different area of the Gulf of Alaska or lower Cook Inlet. Most samples were collected under or adjacent to visible oil slicks or patches of mousse on the sea surface. Sampling depths were 1, 3, 10, and occasionally 2 and 5 meters below the water surface. In the nearshore water quality studies, water samples were collected at or near the water surface and at 1 and 9 meters below the water surface in shallow water near oiled shorelines (within 100 meters).

Sampling methods, sample-handling procedures, quality assurance/quality control, and analytical methods were similar to those described above for the Prince William Sound studies.

ANALYTICAL RESULTS

The focus of the discussion here is on the potentially toxic VOAs and PAHs in the water column of the Gulf of Alaska. As in the water quality studies in Prince William Sound, nearly all the water samples analyzed for PHC (92 percent) contained concentrations below the method detection limit of 50 ppb. The results of these analyses are discussed further in the Appendix. Only six TPH analyses were performed on water samples from these studies, all resulting in nondetectable values.

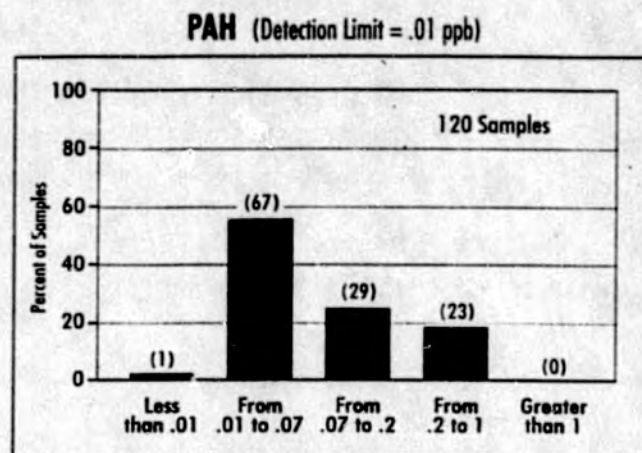
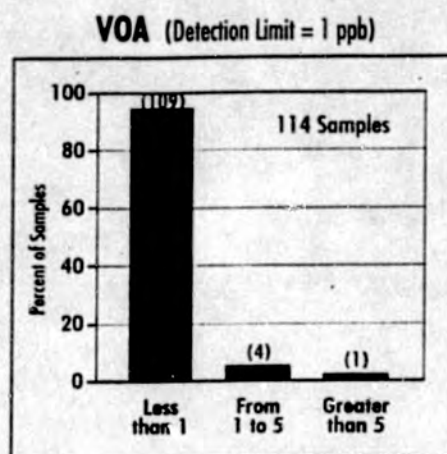
- **Volatile Organic Analytes (VOA)**

A total of 457 water samples (plus 271 quality control samples) were analyzed for VOA as part of the three Gulf of Alaska water quality studies. About 96 percent (109 samples) of the water samples for VOA analysis from the Gulf of Alaska Offshore Water Quality Study contained less than 1.0 ppb (Figure 11). Only one sample contained more than 5 ppb VOA. This sample contained 6.1 ppb VOA and was collected midway between the western tip of the Kenai Peninsula and the Barren Islands. The average concentration of VOA in all offshore water samples combined was 0.15 ppb.

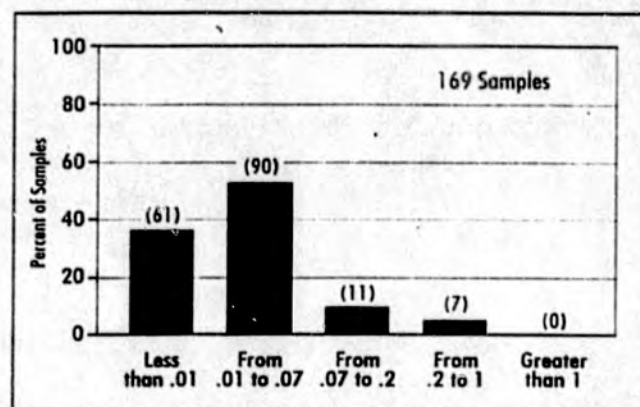
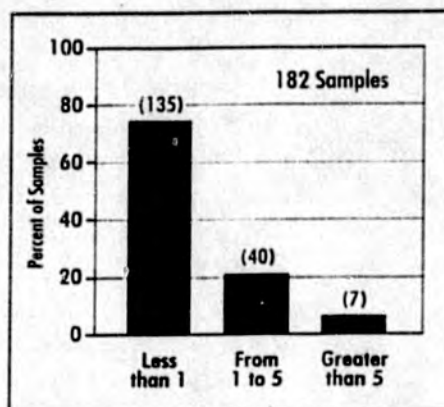
Concentrations of VOA were below the method detection limit of 1 ppb in more than 74 percent (135 samples) of the water samples collected for VOA analysis as part of the Kenai/Cook Inlet Nearshore Water Quality Study (Figure 11). Just under 4 percent of the samples (7 samples) contained more than 5 ppb VOA. The highest VOA concentration measured was 25 ppb in a water sample collected at the water surface in Chugach Bay in mid-August. A replicate sample contained 8.6 ppb VOA. The VOAs in these samples probably were derived from a source other than the spilled crude oil, since these volatile components do not remain long after a spill.

More than 81 percent (131 samples) of the 161 water samples collected as part of the Kodiak/Alaska Peninsula Nearshore Water Quality Study for analysis of VOA contained less than 1.0 ppb (Figure 11). Only two samples contained more than 5 ppb VOA. One of these, a surface water sample from Perevalnie Passage, contained 9.2 ppb

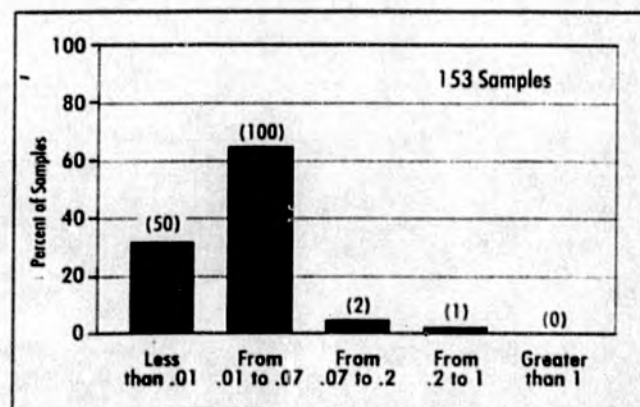
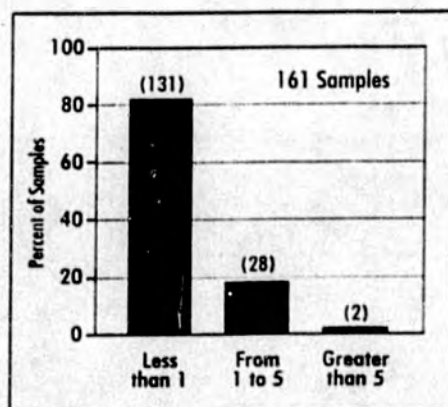
**Offshore
Gulf of Alaska**



**Nearshore
Kenai/Cook**



**Nearshore
Kodiak/Alaska
Peninsula**



VOA Concentration Range (ppb)

PAH Concentration Range (ppb)

Figure 11. Distributions of Volatile Aromatic (VOA) and Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Western Gulf of Alaska)

VOA. The average VOA in all water samples combined from the Kodiak/ Alaska Peninsula Nearshore Water Quality Study was 0.7 ppb.

• **Polycyclic Aromatic Hydrocarbons (PAH)**

A total of 452 water samples (plus 307 quality control samples) were analyzed for PAH as part of the three Gulf of Alaska water quality studies. Results of analysis of water samples for PAH from these studies are summarized in *Figure 11*. Concentrations of total PAH in the offshore water column of the western Gulf of Alaska were quite low in April and May of 1989 at the time when surface oil slicks and mousse were moving through the area. The average for all 120 water samples collected during the Gulf of Alaska offshore water quality study for PAH analysis was 0.12 ppb. No water samples contained more than 1.0 ppb PAH. The highest concentration measured was 0.99 ppb in a sample collected east of Perl Island in early April from 9 meters below the water surface. Over eighty percent (97 of 120 samples) of the water samples contained less than 0.20 ppb PAH.

Approximately 34 percent of the water samples (111 of 322 samples) collected for PAH analysis during the nearshore water quality studies in the Gulf of Alaska contained less than 0.01 ppb PAH (*Figure 11*). Ten surface water samples collected adjacent to a heavily oiled site in Morning Cove on Ragged Island near the Kenai Peninsula during a storm in August contained 2.0 to 4,320 ppb total PAH. These samples also contained 2.2 to 2,800 ppm PHC and were reported by the field team to contain mousse material washing off the shore; they are not included in *Figure 11*. No other water samples from these two studies contained more than 1.0 ppb PAH. The average PAH concentration in water samples from the Kenai/Cook Inlet Nearshore Water Quality Study was 0.034 ppb; the average PAH concentration in water samples from the Kodiak/Alaska Peninsula Nearshore Water Quality Study was 0.019 ppb.

GULF OF ALASKA RESULTS SUMMARY

Concentrations of VOA and PAH in offshore and nearshore waters of the western Gulf of Alaska in areas affected by the spilled oil were uniformly very low during the spring and summer of 1989. Average concentrations of both VOA and PAH in water samples from the Gulf of Alaska were comparable to concentrations in water samples from Prince William Sound. A small number of surface water samples collected off a heavily oiled shore on the Kenai Peninsula during a storm contained very high concentrations of both PAH and PHC in the form of mousse and were not included in concentration averages because they contained free (undissolved) oil.

OIL SHEENS ON THE WATER SURFACE

INTRODUCTION

The results of the extensive water quality monitoring efforts discussed in the previous sections of this report indicate that concentrations of petroleum hydrocarbons in the water column throughout Prince William Sound, particularly since late April of 1989, have been sufficiently low that it is unlikely that there have been any adverse biological effects in marine plants and animals living in the water column. Oil washing off oiled shorelines during tidal flushing or storms may form a thin film (sheen) of oil on the water surface. Most of the highest petroleum hydrocarbon concentrations measured in the water quality studies were in samples collected at the water surface and probably contained material from surface sheens. Therefore, studies were initiated in October, 1989 to sample and analyze petroleum hydrocarbons in sheens observed in some heavily oiled bays in western Prince William Sound.

BACKGROUND

Poorly soluble organic materials, including petroleum, when added to water, tend to form a film on the water surface. A very thin film is colored and, therefore, is called a sheen. The color of a sheen changes with its thickness. A rainbow-colored sheen of petroleum is about three ten-thousandths of a millimeter thick (0.3 micrometers). By comparison, a typical sheet of paper is more than 450 times thicker than a rainbow sheen. Thinner sheens are silvery or blue; thicker sheens tend to have dull colors. Sheens thicker than a few thousandths of a millimeter (greater than about 2 micrometers) take on the color of the material forming the sheen and usually are called slicks. Table 1 illustrates the relationship between the color and thickness of a sheen or slick. Because rainbow sheens are so thin, they contain very little petroleum per unit area of water surface. A tablespoon of oil would form a rainbow sheen of about 625 square feet (a square 25 feet on a side).

Crude oil is not the only source of sheens in Prince William Sound. Natural organic material from decaying vegetation or from heavy schooling

of some fish, such as herring, can cause sheens that are difficult to distinguish from sheens caused by oil. Refined petroleum products such as gasoline, diesel fuel and lubricating oil readily cause sheens. Normal boat operations, particularly pumping of bilges, frequently produce oil sheens. In fact, Hodgson (1990) reported that tests performed by the National Oceanic and Atmospheric Administration, National Marine Fisheries Service in 1989 revealed that some fisheries in Prince William Sound were closed not only because of oil sheens from the crude oil spilled in the accident, but also because of sheens that were later shown to be bilge oil, diesel oil, and hydraulic fluid, and not related to the spill. That sheens in Prince William Sound result from various sources was also demonstrated by the Exxon sheen surveillance overnight program during 1990. As reported during weekly Exxon/agency (Alaska Department of Environmental Conservation and Coast Guard) meetings, by late summer only a small percentage of sheens observed were identified to be oil from the spill.

Table 1. Approximate Thickness of Crude Oil on the Sea Surface Based on Appearance (Color). (National Research Council, 1985)

Appearance	Approximate Oil Thickness (Micrometers)*
Barely visible	0.05
First trace of color (blue/silver)	0.15
Bright rainbow colors	0.30
Dull colors	1.0
Yellowish brown	10.0
Light brown or black, easily visible from aircraft	100.0
Thick dark brown, black, or orange emulsion (mousse)	1,000.0

*A typical page is about 140 micrometers (millionth of a meter) thick.

Regardless of the source, sheens typically are small, often containing no more than a few ounces to a few gallons of oil, and patchy in distribution. They usually are short-lived. Oil sheens dissipate rapidly due to natural weathering processes, including physical dispersion by breaking waves, evapora-

tion, degradation by the abundant bacteria living at the sea surface, photo-oxidation by sunlight, and dissolution into the water beneath the sheen.

COMPOSITION AND ENVIRONMENTAL SIGNIFICANCE OF CRUDE OIL SHEENS

In the sheen study, water samples were collected in one-liter bottles from 10 heavily oiled bays in western Prince William Sound in October, 1989. Surface water samples were collected in sheens whenever they were observed. The sampling method collected water from approximately the upper centimeter (0.4 inches) of the water column, including an area of the water surface of about 1,000 square centimeters (155 square inches). The sampling method produced samples that allowed the composition of the sheen to be determined and provided a semiquantitative estimate of the amount of hydrocarbons present per unit area of water surface. Fifty-three samples (including 14 quality control samples) were submitted for PAH analysis and 57 samples (including 15 quality control samples) were submitted for PHC analysis.

The concentrations of total PAH in 39 sheen samples ranged from below the detection limit (about 0.01 ppb) to 18.4 ppb (Figure 12). The sample containing 18.4 ppb was obtained from Northwest Bay, a site identified in the shoreline monitoring study, discussed earlier, as having high concentrations of PAH and VOAs in surface water samples. Fifteen percent (6 samples) of the samples contained more than 1.0 ppb PAH. Over 69 percent (27 samples) of the samples, however, contained less than 0.2 ppb total PAH.

Seventeen percent (7 samples) of 42 sheen samples analyzed for PHC contained more than 100 ppb PHC (Figure 12). Seventy-nine percent (33 samples) contained less than 50 ppb PHC. The highest concentration of PHC measured was 2,470 ppb in the same sample that contained 18.4 ppb PAH. Generally, there was a good correlation between the concentrations of PAH and PHC in the sheen samples.

By comparison, the concentrations of PAHs, measured as chrysene (a PAH) equivalents, in sheens collected from the open Atlantic Ocean near Bermuda were in the range of 0.4 to 3.04 ppb (Knap et al., 1986). These concentrations can be considered open ocean background values.

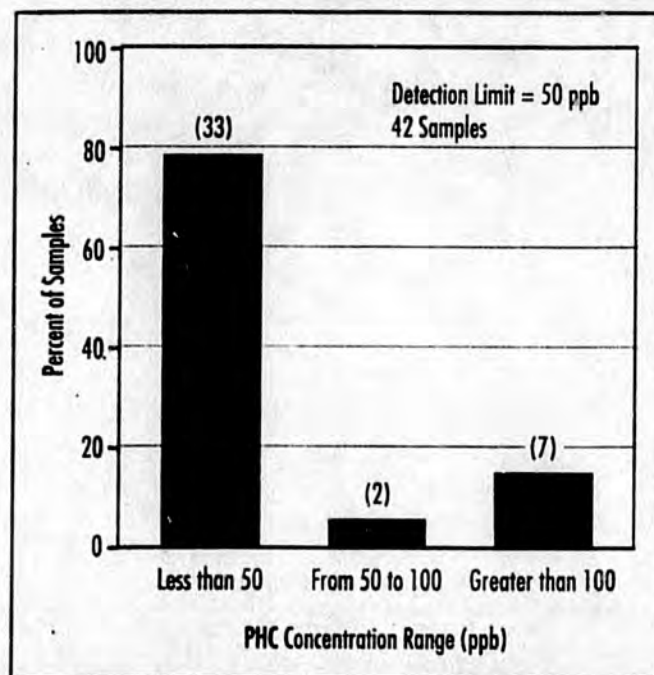
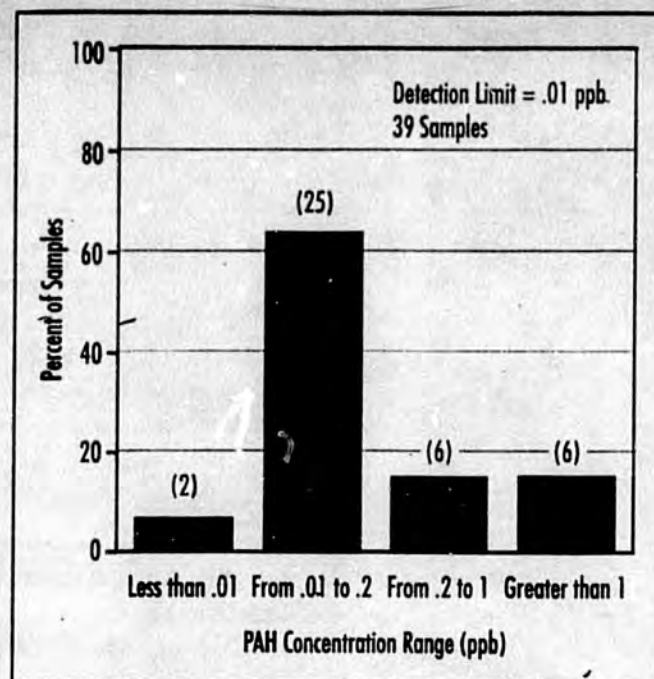


Figure 12. Distributions of Polycyclic Aromatic Hydrocarbon (PAH) and Petroleum Hydrocarbon (PHC) Analyses in Sheens from Bays in October, 1989 (Western Prince William Sound)

Careful evaluation of the PAH composition of the most concentrated sheens revealed that they contained PAHs from two different sources. Most of the PAHs were from highly weathered North Slope crude oil (the spilled oil). However, there were also relatively high concentrations of several PAHs that are found almost exclusively in PAH

assemblages produced during combustion of fossil fuels. These PAHs probably were derived from engine exhaust soot.

Due to the sampling method, it is uncertain exactly where the PAHs were distributed in the upper one centimeter of the water column. One hypothesis is that they were distributed throughout the upper one centimeter. A more likely hypothesis is that the bulk of the PAHs are concentrated in the sheen itself. This latter hypothesis is supported by the current understanding of how poorly soluble organic chemicals like PAHs become distributed between the water column and the air/water interface (Valsaraj, 1988).

A great many species of organisms live on or just below the surface of the ocean. Neuston are bacteria, plants, and animals that spend all or part of their life cycles associated with the water surface (Hardy, 1990). Included among the neuston are the eggs and larvae of several species of fish and invertebrates that spend the remainder of their lives deep in the water column or on the bottom of the sea. Walleye pollock and several species of soles are examples of commercially important Alaskan species of fish whose eggs and early larvae are neustonic.

A wide variety of potentially toxic organic chemicals and metals of natural and man-made origin tend to collect and accumulate at the air/sea interface. Although these accumulations of materials have been shown in laboratory tests to be toxic to neustonic organisms, the organisms apparently are able to adapt rapidly to chemicals in the microlayer (Hardy et al., 1987 a,b; Riznyk et al., 1987). Rich and diverse neuston communities can be found even in industrial ports where sheens contain high concentrations of toxic chemicals, including PAH.

In Puget Sound, Washington, there was a poor correlation between the high concentration of aromatic hydrocarbons in surface sheens and survival of the neustonic eggs of sand sole (Hardy et al., 1987 a,b). The mean concentration of total aromatic hydrocarbons in Puget Sound sheens was 132 ppb, and the maximum concentration was 8,030 ppb. In spite of this very high concentration, thirty-six percent of the fish eggs exposed to the sheen containing 8,030 ppb total aromatics (as well as high concentrations of PCBs, pesticides, and metals) produced normal larvae. Phytoneuston (microscopic plants living at the sea surface) were able to adapt within two days to artificial sheens

containing 1,000 ppb fluoranthene, another PAH (Riznyk et al., 1987). Thus, neustonic organisms do not appear to be particularly sensitive to PAH in surface sheens.

The concentrations of PAH measured in sheens from oil-contaminated bays in western Prince William Sound are all well below concentrations of aromatic hydrocarbons measured in sheens from Puget Sound. Because the sampling methods used in this study are only semiquantitative, actual PAH concentrations in some sheens could be higher than estimated here. However, the concentrations estimated in this study for sheen-covered waters are orders of magnitude below those found in the field or laboratory to cause harmful effects in the sensitive early life stages of marine organisms.

It is extremely unlikely that the permanent neuston (the organisms whose entire life cycle is spent at the water surface), upon which some commercially important species feed, or the temporary neuston (including the eggs and larvae of some commercially important fish and shellfish) of Prince William Sound are being adversely affected by the patchy, short-lived sheens of weathered crude oil occasionally being observed in parts of western Prince William Sound. If some of the neuston directly under a sheen were killed through direct contact and coating with sheen hydrocarbons, they would be replaced rapidly by influx of neuston from areas adjacent to the sheen and by the rapid reproduction of a majority of the permanent neuston organisms.

SHEEN SAMPLING AND ANALYSIS SUMMARY

Oil sheens are patchy, short-lived phenomena in parts of western Prince William Sound. Surface waters covered with oil sheens derived from spilled oil washing off oiled shores contain low concentrations of highly weathered crude oil. Measured concentrations of the PAH and PHC fractions of weathered crude oil in sheen-covered surface waters are very low, usually less than a few parts per billion, and rarely to 18 ppb and 2,000 ppb, respectively. These concentrations are well below concentrations found in laboratory and field studies to cause deleterious effects in organisms (neuston) occupying the sea surface. Therefore, it is unlikely that marine organisms in Prince William Sound are being adversely affected by sheens of spilled crude oil.

SUMMARY OF WATER QUALITY IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

Concentrations of PAH were the best indicators of the degree of contamination of the spilled crude oil in the water column of Prince William Sound and the Gulf of Alaska. A total of 1,683 water samples were analyzed for PAH as part of the seven water quality studies discussed in this report. Thirteen of these samples contained large amounts of mousse, tar balls, or sheen material. The PAH concentrations in them were not representative of PAH concentrations in the water column, and so they are not included in this summary. These samples were described and discussed in earlier sections of this report. More than 12 percent (208 samples) of the remaining 1,670 water samples from all water quality sampling stations in Prince William Sound and the Gulf of Alaska contained less than 0.01 ppb PAH (Figure 13). Sixty-three percent of the samples (1,050 samples) contained between 0.01 and 0.07 ppb PAH. Only

27 water samples (1.6 percent) contained more than 1 ppb PAH. Most of the water samples (16 samples) containing more than 1 ppb PAH were collected at nearshore water quality sites in Prince William Sound. With the exception of a small number of surface water samples probably containing sheen material, mousse, or tar balls, the nearly 1,700 water samples collected from Prince William Sound and the western Gulf of Alaska during the year after the spill contained concentrations of PAH well below concentrations known to be toxic or cause adverse sublethal effects in marine organisms.

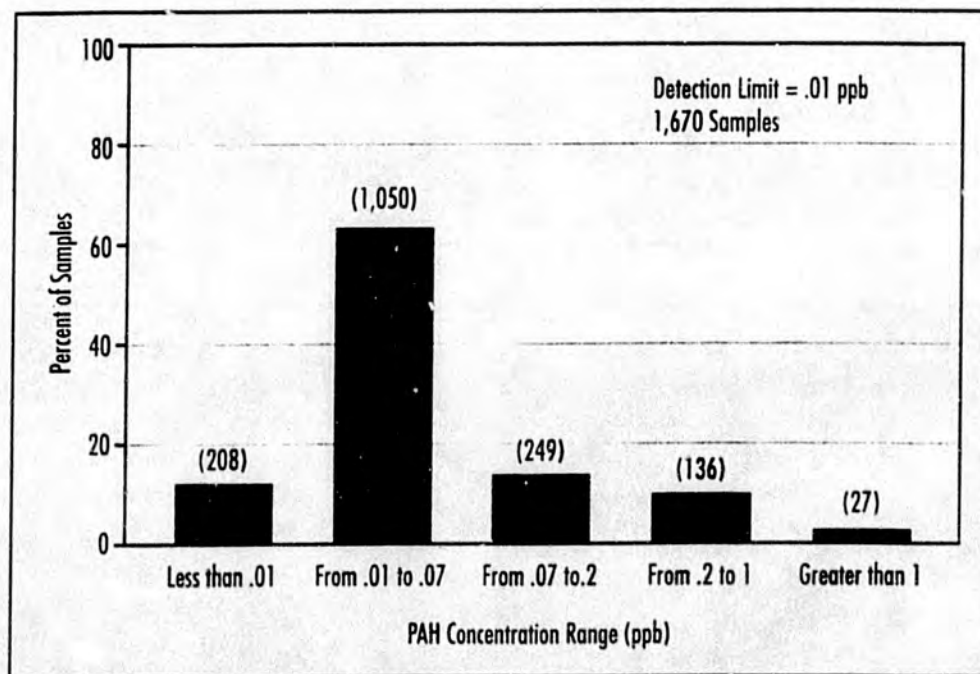


Figure 13. Distribution of Polycyclic Aromatic Hydrocarbon (PAH) Analyses (Prince William Sound and Western Gulf of Alaska)

BIOLOGICAL EFFECTS OF CRUDE OIL ON MARINE ORGANISMS IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

INTRODUCTION

As discussed in earlier sections of this report, the concentrations of petroleum hydrocarbons measured in more than 5,000 samples of seawater from nearshore and offshore waters of Prince William Sound and the western Gulf of Alaska in 1989 and early 1990 are well below concentrations that have been shown in laboratory and field studies to be lethal to marine organisms, including commercially important species. This conclusion is based on a review of the vast amount of information published in the last two decades on the acute, chronic, and sublethal effects of crude and refined oils and their constituent chemicals in marine plants and animals. This section of the report provides background information on the toxicity of crude oil and relates the published information to the concentrations of petroleum hydrocarbons actually measured in the water column of Prince William Sound and the western Gulf of Alaska.

DEFINITIONS

Crude oil toxicity is defined as imparting a deleterious effect, lethal or sublethal, to an organism, population, or community (National Research Council, 1985). The toxicities of different crude oils vary widely, primarily for three reasons:

- Crude oils vary widely in chemical composition and physical properties. Light and medium weight (low viscosity) crudes containing abundant PAHs (e.g., naphthalene and phenanthrene) are more toxic than heavy crudes that are deficient in PAHs.
- After a spill, most crude oils weather quite rapidly. During weathering, the most toxic fractions of the oil are lost through evaporation to the atmosphere or dissolution in the water column. Other components of the oil are broken down by the action of marine bacteria and sunlight. Through weathering, the chemical composition, viscosity, and toxicity of a spilled crude oil change continuously.

- Marine plants and animals differ widely in sensitivity to crude oil and the different components of crude oil. In most but not all cases, the early life stages of marine animals are more sensitive to crude oil than are juvenile and adult life stages (National Research Council, 1985).

Care must be taken in comparing the results of oil toxicity tests (Neff and Anderson, 1981). Many studies use refined petroleum products, such as diesel fuel, which usually are substantially more toxic than crude oils (Anderson et al., 1974; Rice et al., 1985). Results of studies with refined oils cannot be extrapolated to predict effects of a crude oil spill. In many earlier studies, hydrocarbon concentrations were reported as the total volume of oil added to a unit volume of water. However, only a small fraction of the oil added to water actually goes into solution. It is widely accepted that the fraction of the oil contributing the most to its toxicity to water column organisms is the fraction that is actually in solution in the water (the so-called water-soluble or water-associated fraction, usually abbreviated as the WSAF). To obtain meaningful results for laboratory toxicity effects tests, the actual exposure concentration must be measured by quantitative analytical methods.

Fortunately, most of the recent biological effects studies have been performed with the WSAF and actual exposure concentrations have been measured. A majority of the petroleum hydrocarbons in the WSAF are the same as those measured by the VOA and PAH methods discussed above. Thus, tests in which effects are reported in relation to measured concentrations of the WSAF can reasonably be compared to concentrations of VOAs and PAHs measured in the water column of Prince William Sound.

The results of laboratory toxicity tests usually are reported as the LC50 or EC50 value after a given exposure period to the crude oil (Neff, 1987). The LC50 is the median lethal concentration (the concentration estimated to cause 50 percent mortality among test organisms); the EC50 is the median effective dose (the concentration

causing a particular non-lethal response in 50 percent of test organisms). For example, a 96-hour LC50 of 10 ppm total PAH means that exposure of a group of test organisms for 96 hours to 10 ppm total PAH resulted in 50 percent mortality.

Both static and flow-through tests have been performed in the laboratory with crude oils. Static tests are performed in closed systems (e.g., an aquarium) containing a WSF of the test oil. Most of the hydrocarbons are lost rapidly from the water in static systems, leading some investigators to replace the WSF with freshly prepared WSF periodically during the test. In the flow-through system, the WSF is prepared continuously and dosed into the exposure tanks containing the test organisms. These systems are able to maintain constant exposure concentrations for long periods of time, and the results of such tests are easier to interpret.

Near an oil spill or under a surface oil sheen, organisms in the water column are exposed to continuously changing concentrations of petroleum hydrocarbons, an exposure regime that cannot be simulated easily in the laboratory. The dose of a chemical to a marine organism has two components, the concentration of the chemical, and the duration of exposure to that concentration. In recognition of this and to make comparisons between doses administered in the laboratory and field more realistic, Anderson et al. (1984) and McAuliffe (1987) have recommended that dose be expressed as the product of exposure concentration and hours of exposure to that concentration (e.g., exposure to a petroleum concentration of 2 ppm for 24 hours would be expressed as a dose of 48 ppm-hrs or 2 ppm-days).

BIOLOGICAL EFFECTS

Three classes of pelagic (living in the water column) organisms are of particular concern with respect to effects of the spilled oil on the Prince William Sound/Gulf of Alaska ecosystem. These are the phytoplankton, the zooplankton, and the pelagic fish. All are concentrated primarily in the upper 20 to 30 meters (65 to 98 feet) in the zone of maximum penetration of sunlight. The phytoplankton and zooplankton are important direct or indirect sources of food for pelagic fish of commercial importance such as herring and salmon.

PHYTOPLANKTON

Phytoplankton are small, usually microscopic plants (usually algae) that are the primary producers at the base of most marine food webs. The toxicity of petroleum to phytoplankton usually is measured as a change in growth rate (rate of cell division) and photosynthetic activity (expressed as an EC50) of a single species or a natural assemblage, compared to controls (National Research Council, 1985; Capuzzo, 1987). Toxicity of a particular oil seems to be related to the concentration in the oil of low molecular weight aromatic hydrocarbons (VOAs and PAHs) (Vandermeulen and Ahearn, 1976). Decreases in growth rate or inhibition of photosynthesis have been reported at concentrations of the WSF of crude oil in the range of 1,000 to 10,000 ppb. However, exposure to lower concentrations of crude oil in the range of 5 to 100 ppb in the laboratory and field (particularly after weathering has removed the most volatile components) often results in stimulation of growth and respiration (Prouse et al., 1976).

Several attempts to document decreases in the abundance of phytoplankton or changes in the species composition of natural phytoplankton communities following major crude oil spills have failed (National Research Council, 1985). However, there were decreases in phytoplankton abundance in nearshore and estuarine waters near the wreck of the *Amoco Cadiz* for a few weeks immediately after the spill. The observations of either no effects or just temporary effects of spilled oil on phytoplankton are primarily a result of two factors. First, the doubling time of the algae (time for a single cell to divide into two new cells) is very rapid (9 to 12 hours), and second, replacement from adjacent, unaffected populations is efficient due to the normal mixing of water masses. Because of these factors, even if a large number of phytoplankton cells is adversely affected, their abundance in the affected area returns to normal almost immediately (National Research Council, 1985).

The concentrations of water-soluble aromatic hydrocarbons (VOAs and PAHs) measured in the water column of Prince William Sound and the Gulf of Alaska during 11 months after the spill were always much lower than the concentrations that have been shown to cause adverse effects in phytoplankton and usually lower than even the concentrations (5 to 100 ppb) shown to stimulate phytoplankton growth. Therefore, it is highly

likely that the very rich phytoplankton communities of Prince William Sound were largely unaffected by the spilled oil.

ZOOPLANKTON

Zooplankton are animals (usually very small) that drift with the prevailing water currents. Included among the zooplankton are a wide variety of different species, representing a diversity of feeding types and life histories. There are permanent members of the zooplankton community that spend their entire life cycles as plankton. The dominant permanent zooplankton animals, such as copepods (small crustaceans sometimes called the insects of the sea because of their vast numbers) feed primarily on the phytoplankton and, like the phytoplankton, have short life cycles and rapid reproduction rates.

Also included among the zooplankton are temporary zooplankton that spend only a part of their life cycles in the zooplankton community. These include the eggs and larvae of many pelagic and bottom-living fish and invertebrates, including all the commercially-important fish and shellfish species of Prince William Sound except the salmon. Thus, the zooplankton are important both as links in the food web to commercially important fishery species and as the young life stages of many of these important species.

In most, but not all cases, the early embryo/larval life stages of marine animals are more sensitive than later life stages to chemical contaminants, including spilled oil (Rosenthal and Alderdice, 1976). Acutely lethal concentrations (measured as the 24-, 48-, or 96-hour LC50) of crude oils to both permanent and temporary zooplankton, as summarized by Capuzzo (1987), fall in the range of 200 to greater than 43,000 ppb total petroleum hydrocarbons. Corner (1978) and Johnston (1984) reported acutely lethal concentrations of the WSF of crude oil in the range of 100 to 10,000 ppb for copepods and several other permanent members of the zooplankton community.

Sublethal responses, such as decreases in growth rate, usually were observed at exposure concentrations only slightly lower than to about one-tenth the concentrations that were lethal (Anderson et al., 1987a; Neff, 1987). When returned to oil-free water, fish and invertebrates nearly always recover quickly and completely from most sublethal effects. Survival of mussel larvae following exposure for 24 hours to 10 ppb

naphthalene (a major component of the PAH fraction of oil) was about half that of unexposed control larvae (Malins et al., 1982). This concentration is more than a factor of ten higher than any naphthalene concentration measured in the water column of Prince William Sound or the Gulf of Alaska.

Excluding samples that obviously contained mousse or tar balls, as discussed in earlier sections of this report, concentrations of total PAH in the water column of Prince William Sound and the Gulf of Alaska have remained below 1 ppb, with few exceptions. Concentrations up to about 30 ppb were observed in surface samples (probably containing sheen material) in just a few cases and these higher concentrations appeared to be very short-lived. Therefore, it is highly likely that adverse impacts of the spilled oil on zooplankton, including early life stages of fishery species, have been minimal. Any losses of permanent zooplankton organisms would have been made up rapidly by reproduction or influx of animals from unaffected areas (National Research Council, 1985). Any losses of eggs and larvae of important food web or fishery species would have been very localized, affecting only a very small fraction of the individuals available for recruitment to the adult stocks.

FISH

Adult fish are not particularly sensitive to oil. Effects on adult fish usually are reported at oil (WSF) concentrations of 1,000 to 50,000 ppb, whereas growth of the young fry of some species of salmon was affected by oil concentrations in the range of 700 to 5,000 ppb (Vandermeulen and Capuzzo, 1983; Rice et al., 1985). The acutely lethal concentration of the WSF of Cook Inlet crude oil for pink salmon fry was about 1,700 ppb (Rice et al., 1979). There have been some reports of sublethal effects on eggs and larvae of a few species of fish during chronic exposures lasting several days to aromatic hydrocarbon concentrations of about 10 ppb (Capuzzo, 1987). Coho salmon and starry flounder (both Alaskan species) exposed for five days to 100 ppb of the WSF of Prudhoe Bay crude oil developed gill lesions resulting from loss of surface cells (Roubal et al., 1977). Growth rate of Pacific herring larvae was depressed during exposure for 14 days to 300 ppb of the WSF of Cook Inlet crude oil (Carls, 1987). Homing migrations of several species of Pacific salmon do not appear to be very sensitive to effects

of crude oil (Nevissi and Nakatani, 1990). Different species of salmon avoided water containing 1,600 to 4,600 ppb of the WSF of crude oil during their upstream migration. Homing of coho salmon in seawater was not affected by preexposure of the salmon to 1,600 ppb of the WSF of crude oil.

Because of concerns about the potential effects of major oil spills on commercial fisheries, many attempts have been made after other spills to document adverse effects on commercially important fish and fisheries. Fish kills have been reported after some oil spills, though it is important to note that there have been no verified reports of fish kills in Prince William Sound, Alaska attributable to the oil spill. Fish kills were reported following other spills, and the most affected were shallow-water and bottom-living species (Teal and Howarth, 1984). Large kills of offshore pelagic fish species have not been reported. Thus, direct effects of oil on adult fish populations probably are small and have little or no effect on the fishery as a whole.

Although the commercial fishery catch along the Brittany coast of France declined for a few months after the *Amoco Cadiz* oil spill, it appears that the decline was due primarily to a lack of fishing effort while the fishermen were harbor-bound to avoid oiling their boats and fishing gear (Anderson et al., 1983). However, there was a decline lasting for one year in the reproduction rate of a species of commercially important flatfish (a bottom-dwelling species) inhabiting some heavily oiled estuaries near the spill site (Conan, 1982).

The two most important commercial fisheries species in Prince William Sound are Pacific herring and pink salmon and these fish were not significantly affected by oil spilled in the Sound as evidenced by spawning activity and fishing results. Results of aerial surveys flown by field biologists from the Alaska Department of Fish and Game confirm that spawning activity of herring in shallow intertidal and subtidal waters of the Sound in 1989 and 1990 was comparable to historical averages for the year immediately preceding the spill (Maki, 1991). There was an all-time record catch rate of herring in Prince William Sound in 1990. The pink salmon which emerged from the intertidal sediments and hatcheries of the Sound as fry into the spill covered waters of Spring, 1989 returned to the Sound and were caught in record numbers in 1990. The commercial harvest exceeded 44 million pink salmon, about 14 million fish

more than the previous record Prince William Sound harvest in 1987.

Death of fish eggs and larvae was reported after two spills (the *Argo Merchant* and the *Tsesis* spills: both spills involved refined oil products) (Teal and Howarth, 1984). These mortalities were associated with sheens and slicks of fresh, unweathered oil immediately after the spills. They affected the floating eggs and larvae of a few species over small areas but had no measurable effect on recruitment to the adult stocks. There have been no reports of death of fish eggs and larvae in the field following exposure to weathered crude oil, like that present in sheens washing off shores in Prince William Sound. These weathered crude oil sheens are likely to be much less toxic than sheens of fresh crude oil or refined oil products because the weathered oil contains much lower concentrations of volatile, toxic aromatic hydrocarbons than unweathered oil.

Tainting of fish by oil was reported following a few large spills (*Amoco Cadiz*, *Argo Merchant*, and *Ekofisk Bravo*), but only in small numbers and a small percentage of the fish analyzed (Teal and Howarth, 1984). Except for very slightly elevated hydrocarbon levels in shellfish (Maki, 1991), no such tainting of the edible tissues of fish has been reported in Prince William Sound. In those cases where it was reported after other spills, this tainting of fish occurred for only a short time immediately after the spill. Detectable concentrations of potentially toxic PAH persisted in the edible tissues of commercial fish and shrimp species for no more than a few months after even massive spills, such as the *Amoco Cadiz* spill (six times larger than the *Exxon Valdez* spill). This is due to the fact that fish and shrimp have the ability to very rapidly break down (detoxify) aromatic hydrocarbons and excrete them in the urine or feces (Neff, 1979).

Based on these observations from Prince William Sound and other spills, it is unlikely that the oil spill affected fishery populations in Prince William Sound or the Gulf of Alaska. Any effects would have occurred in the few weeks immediately after the spill and would have been very localized and minor relative to fishery stock sizes and future catches. As discussed above, no such effects on commercial fishery catches were observed in 1989 and 1990. It is extremely unlikely that any long-term effects directly attributable to the spill will be observed in terms of reduction in reproduction and early survival of fisheries species or in decreased

fishery catch of any commercial species.

This conclusion is supported by the large difference in the concentrations of petroleum hydrocarbons required to cause mortalities or deleterious sublethal effects in juvenile and adult fish and the concentrations of petroleum hydrocarbons measured in the water column of Prince William Sound and the Gulf of Alaska. In most cases the concentrations measured were at least one-thousand-fold lower than concentrations that are known to be harmful to fish. Thus, the margin of safety for fish in Prince William Sound and the Gulf of Alaska was very large and grew larger as the concentrations of petroleum hydrocarbons in the water column decreased over the summer and fall of 1989.

As discussed above, another way to extrapolate from results of laboratory biological effects studies to predictions of possible effects at the concentrations of petroleum hydrocarbons observed in the water column is to express the effects in terms of both exposure concentration and exposure duration. McAuliffe (1987) summarized data from Anderson et al. (1987b) for Prudhoe Bay crude oil and from Rice et al. (1979) for Cook Inlet crude oil in this way (Table 2). The median lethal doses of Alaskan crude oil reported in these papers are many-fold higher than the estimated doses of aromatic hydrocarbons (expressed as concentrations of VOAs or PAHs) present in the water column of Prince William Sound (Table 3). An estimated safety factor can be calculated by dividing the median lethal doses (Table 2) by the estimated actual doses in the water column (Table 3). Depending on species and estimated dose in the water column, safety factors measured in this way range from 79 (or 15/0.19) to 21,400 (or 62/0.0029).

These comparisons between harmful concentrations of petroleum hydrocarbons and concentrations actually measured in the water column of Prince William Sound and the Gulf of Alaska provide convincing evidence that the amounts of oil that were in the water column, even in the first few weeks after the spill, were much lower than concentrations known to be harmful to commercial fisheries species. Concentrations of petroleum hydrocarbons dropped to near background levels offshore by the end of May, 1989. In protected bays, particularly those whose shores were heavily oiled, slightly elevated, though still nontoxic, concentrations of petroleum hydrocarbons persist-

Table 2. Doses (Concentration Times Duration-of-Exposure) of Prudhoe Bay Crude Oil and Cook Inlet Crude Oil Causing 50 Percent Mortality in Several Species of Alaskan Marine Animals. (Adapted from McAuliffe, 1987)

Species	Median Lethal Dose (ppm-hr)
Coonstripe shrimp	15
Kelp shrimp	62
Grass shrimp	29
Pacific herring	41
Dolly varden	52
Pink salmon	57
Chum salmon fry	19

Table 3. Doses Based on a 96-hour Exposure to Petroleum Hydrocarbons at Average Concentrations Measured in Prince William Sound.

Measurement	Estimated Dose (ppm-hr)
Peak average offshore VOA (2 ppb)	0.19
Peak average offshore PAH, worst case (0.7 ppb)	0.068
Peak average offshore PAH (0.2 ppb)	0.019
Average VOA, October (0.2 ppb)	0.019
Average PAH, October (0.03 ppb)	0.0029

ed in small areas of the water column (e.g., under slicks) into June, 1989. It is unlikely that these small regions containing slightly elevated concentrations of petroleum hydrocarbons will have any measurable effect on the populations of marine animals living there.

Chronic exposure to petroleum hydrocarbons may produce a wide variety of sublethal biological effects in marine fish and invertebrates. Many of these responses are general responses to an environmental disturbance and may cause no lasting harm unless the disturbance is persistent (National Research Council, 1985). Rice et al. (1985) have studied the sublethal effects of Alaskan crude oils to several species of Alaskan fish and crustaceans. Sublethal responses were elicited by exposure to oil concentrations from about 10 to 50 percent of the acutely lethal concentrations. In most cases, the sublethal responses returned to normal (the animals recovered) very rapidly after the animals were returned to oil-free seawater. The safety factors

discussed above are large enough that it is unlikely that pelagic fish and invertebrate populations in Prince William Sound or the Gulf of Alaska have or will experience any deleterious sublethal responses to the spilled oil.

When fish are exposed to petroleum dissolved or dispersed in the water or bound to sediments, an enzyme system, known as the cytochrome P450 mixed function oxygenase (MFO) system, is induced in the liver and some other tissues (Neff, 1979; Stegeman, 1981). The result is that the amount of the enzymes and their activity increases. Biochemical methods have been developed to determine when MFO activity is induced in fish and this approach has been recommended as a sensitive method for determining exposure of fish populations to oil (Payne, 1984). MFO activity is induced at low concentrations of petroleum PAH, as well as several other chemicals such as polychlorinated biphenyls and PAH derived from combustion sources (Kleinow et al., 1987). However, because of the sensitivity of the MFO system, many natural populations, particularly of bottom living fish, from presumably clean environments show evidence of MFO induction (Stegeman et al., 1987). In addition, MFO activity is affected by many natural variables, such as season, temperature, sex, and stage in reproductive cycle (Kleinow et al., 1987; Edwards et al., 1988). Therefore, induction of MFO activity must be used with caution as a tool for monitoring exposure of fish populations to oil. Induction of MFO is an adaptive response in animals, designed to aid the animal to excrete potentially toxic compounds (Neff, 1985). It is not by itself an indication of existing or pending pathology in the affected animal.

Levels of MFO induction reported in Prince William Sound fish after the spill (Bayliss, 1990) are quite low compared to induced levels found elsewhere (Stegeman et al., 1987). The Coast Guard has indicated that the measurement of enzyme induction, particularly at the low levels reported by Bayliss, is an unproven technique for demonstrating injury to marine species resulting from exposure to hydrocarbons (Ciancaglini, 1990). Payne et al. (1987) have shown that pathological effects possibly associated with MFO induction only occur in heavily contaminated environments in fish that are maximally induced. This was not the case in Prince William Sound or the Gulf of Alaska.

CONCLUSIONS OF BIOLOGICAL EFFECTS STUDIES

Concentrations of petroleum hydrocarbons in the water column of Prince William Sound and the Gulf of Alaska, even in the month immediately after the spill, have consistently remained below concentrations of crude oil hydrocarbons that have been demonstrated in laboratory and field studies to be toxic to or produce sublethal effects in organisms living in the water column. Therefore, harmful effects, if any, of the spill on water column organisms in 1989 and 1990 are expected to be quite isolated, and result in little or no damage at the population or community levels. There is no reason to expect that there will be any harmful long-term effects of the remaining oil in 1991 or beyond on water column organisms, including commercially important herring and salmon populations.

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APPENDIX

UPDATES TO THE APRIL, 1990 WATER QUALITY REPORT

This March, 1991 update to the April, 1990 report expands both the geographic and temporal coverage of available data. Approximately twice as much data as was available in April, 1990 is included. In addition, it was determined that reprocessing a portion of the data was desirable to ensure the methods were comparable among laboratories. Finally, since April, 1990 the cause of a sampling problem identified in that report was clarified.

As indicated in Table A-1, data from three additional sources became available since publication of the April, 1990 report. These include (1) data from offshore studies in Prince William Sound, primarily from the February-March, 1990 offshore water quality survey, (2) additional sample analyses from the two Prince William Sound near-shore water quality studies, and (3) data from the three water quality studies performed in the western Gulf of Alaska. The total number of analytical results more than doubled from 3,053 (including 706 quality control samples) in April, 1990 to 7,532 (including 2,434 quality control samples) in March, 1991. It was felt that a combination of these newly available data, with the data available in April, provide a more comprehensive picture of the status of water quality during the first year after the spill in areas where the spilled oil drifted.

Review of the hydrocarbon concentration data revealed that results of analyses for PAH by one laboratory were consistently lower than the results produced by other analytical laboratories. When the reasons for these systematic differences were identified, the raw PAH data were reprocessed by the quantification methods used by the other analytical laboratories. This was done in order to make all PAH data for water samples consistent and comparable (reprocessing of PAH data is described below).

Hydrocarbon concentrations in seawater and blank samples collected with the water sampler that tended to contaminate samples were reviewed again. Field protocols for use and cleaning of the sampler also were reviewed. It was reaffirmed that, for the offshore Prince William Sound study, due

Table A-1. Comparison of Numbers of Water Quality Analytical Results Available at the Time of the April, 1990 Report and in this March, 1991 Update.

Study	April 1990		March 1991	
	Water	QC	Water	QC
Prince William Sound Offshore Water Quality	1,878	445	2,319	845
Prince William Sound Nearshore Water Quality	430	261	1,342	690
Prince William Sound Nearshore Sheens	39		81	29
Gulf of Alaska Water Quality			1,356	870
Total	2,347	706	5,098	2,434

to the nature of the sample contamination, analytical data for water samples analyzed for VOA, PHC, and TPH were unreliable and, therefore, not useable. However, the PAH data were marginally acceptable. Therefore, PAH data for subsurface water samples collected with the contaminating sampler were used in the updated report.

AVERAGING SETS OF CONCENTRATIONS THAT CONTAIN VALUES BELOW THE NOMINAL REPORTING LIMIT

In the studies of concentrations of petroleum hydrocarbons in the water column discussed in this report, many analyses yielded results below the nominal reporting limit (similar in magnitude to the method detection limit). These analyses resulted in either no observed signal (non-detects) or a slight signal for which a rough estimate of concentration can be given. The analytical laboratories often report these estimates, called J-values, but they are considered less reliable than values above the official reporting limit. When it was necessary to calculate an average value for a group of analytical results, non-detects were given a value of zero, except when a J-value was given. In these cases, the J-value was used in the calculation of the average.

In calculations of average concentrations, if a fraction of the reporting limit had been used instead of zero, the resulting averages would not have been much higher than the values calculated using zeros or J-values for non-detects, because the reporting limits for the VOA and PAH analyses were so low. Therefore, none of the conclusions about the extremely low concentrations of petroleum hydrocarbons in the water column would have been changed by use of a different method for calculating averages.

HANDLING NONREPRESENTATIVE DATA

Approximately 30 percent of the water samples for VOA, PHC, and TPH analysis from the first and second offshore water quality field surveys, performed in late March and early April, are not included in this report. These samples were collected with a sampling device, widely used in physical and chemical oceanographic sampling, that turned out, with the particular solvent used, to be extremely difficult to clean sufficiently for the types of samples being collected (e.g., samples for analysis of petroleum hydrocarbons present in seawater at ultra-trace concentrations). Reagent-grade hexane was used to rinse the sampler between samples. Although the sampler was rinsed again with water after the hexane rinse, a small amount of hexane sometimes remained adsorbed to the inside walls of the sampler and contaminated the water samples with VOAs and saturated hydrocarbons (components of PHC and TPH). Because of this sampler contamination, the quality control samples for the VOA analyses (often called blanks) obtained with this sampler using high-purity water, contained very high concentrations of VOAs, ranging from 12 to 218 ppb; blanks for PHC and TPH also were high. Because the use of this sampling device resulted in contamination of samples of high-purity water, it was decided to exclude VOA, PHC, and TPH data for seawater samples taken with this sampler on the assumption that they were similarly contaminated. The use of this difficult to clean sampling device was discontinued after the first two surveys. Because the hexane rinse did not contain PAH components, PAH blanks from this sampler did not yield excessively high PAH concentrations. Further, since PAHs were the most useful class of petroleum hydrocarbons for monitoring the distribution and fate of the oil in the water column, it was decided to use the PAH data from water samples collected

with this sampler. This same sampler was used to collect some of the water samples for the Gulf of Alaska Offshore Water Quality Study. However, on these surveys the sampler was rinsed with high-purity methylene chloride which did not result in contamination of the sampler with hydrocarbons. Therefore, results for water samples collected with this sampler during the Gulf of Alaska Offshore Water Quality Study were included in this report.

A similar but less severe problem was encountered with a second type of water sampling device. However, results of analyses of water samples collected with this sampler are included in this report. Use of this device was also discontinued after the second field survey. Surface water samples from all field surveys and subsurface water samples from all field surveys and studies after the second Prince William Sound water quality field survey were collected with a third type of sampler that delivered the water directly into a pre-cleaned sample bottle, substantially decreasing the possibility of contaminating the sample. In addition to the sampling device problems, there was one instance in which two field blanks were incorrectly mislabeled as samples. Associated VOA analyses of these two samples are not reflected in averages included in this report.

REPROCESSING OF PAH DATA

It became apparent when chemists began reviewing the large amounts of water quality data now available, that the results of analyses by different analytical laboratories of PAH in water samples showed systematic laboratory-specific differences. Examination of the detailed data reports produced by the different laboratories revealed that the systematic differences were due in large part to differences among the laboratories in the methods used to quantify individual analytes from the gas chromatograph/mass spectrometer traces.

At the beginning of the water quality studies, standard operating procedures (SOPs) were written giving detailed descriptions of the different analytical methods to be used by the analytical laboratories to analyze water quality samples. One of the analytical laboratories used a slightly different interpretation of the SOP for processing raw data to quantify individual alkylated PAH in water samples. This method yielded slightly lower concentrations than the method called for in the SOP. Subsequently, the raw PAH data from this laboratory were reprocessed and

quantified by the method intended in the SOP, so that data from all analytical laboratories would be consistent. The reprocessed data were used in preparing this revised report. Approximately 20 percent of the PAH data was affected by this reprocessing, most often resulting in slight increases in PAH values.

ANALYSIS OF PETROLEUM HYDROCARBONS (PHC) AND TOTAL PETROLEUM HYDROCARBONS (TPH) IN WATER

For completeness, two methods were used to measure the concentrations of total petroleum hydrocarbons in water samples, even though these types of analyses do not provide as good estimates of concentrations of potentially toxic hydrocarbons in the water as do PAH and VOA analyses. In the PHC analysis method, the concentration of total saturated and aromatic hydrocarbons, including hydrocarbons from natural biological sources such as plant waxes, is measured by a sensitive gas chromatographic technique. The TPH analysis method is a rapid, inexpensive method, useful for sample screening, identification of trends, and rapid estimation of hydrocarbon concentrations. The TPH method, based on infrared analysis, measures all hydrocarbons, including those of biological origin, as well as many other poorly soluble organic compounds. The method is not very sensitive (detection limit of about 1,000 ppb, or 1 ppm) and is highly subject to interference by natural biological organic matter in the water. As a result of these limitations, TPH analysis is unsuitable for monitoring extremely low concentrations of hydrocarbons, such as those existing in Prince William Sound and the Gulf of Alaska following the spill.

Prince William Sound:

A total of 990 water samples (including 210 quality control samples) from the offshore water quality field surveys were analyzed for PHC. Two samples containing more than 450 ppm PHC (described on page 10) were not included in the PHC concentration distribution because they contained mousse or tar balls. As shown in Figure A-1, concentrations of PHCs were below the method detection limit of about 50 ppb in 89 percent of the samples (695 of 778 water samples). Only 23 samples (3 percent) contained more than 100 ppb of PHCs. The highest concentration was

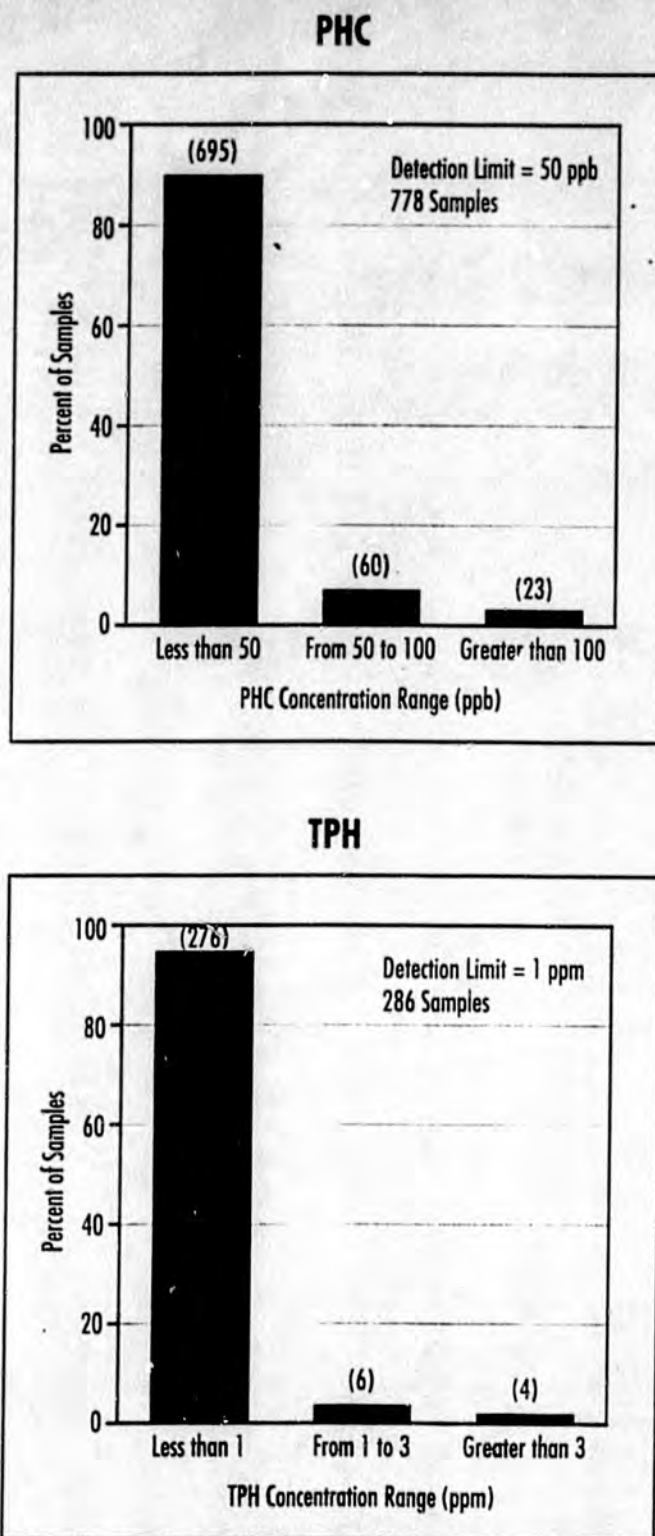
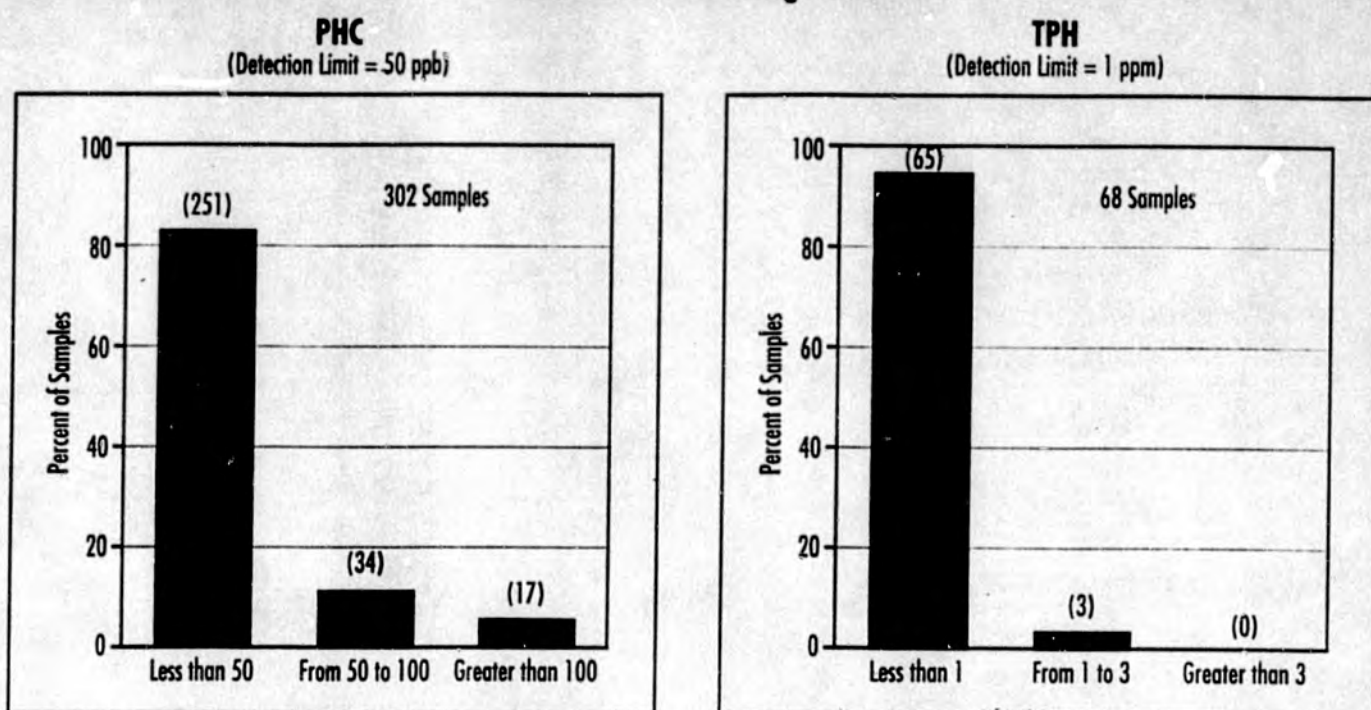


Figure A-1. Distributions of Petroleum Hydrocarbon (PHC) and Total Petroleum Hydrocarbon (TPH) Analyses (Offshore Prince William Sound)

1,000 ppb. Thus, the trend for concentrations of total petroleum hydrocarbons as measured by the PHC technique is similar to the trends in concentrations of VOAs and PAHs. Concentrations of total petroleum hydrocarbons were uniformly low

Shoreline Monitoring Sites



Shoreline Treatment Monitoring Sites

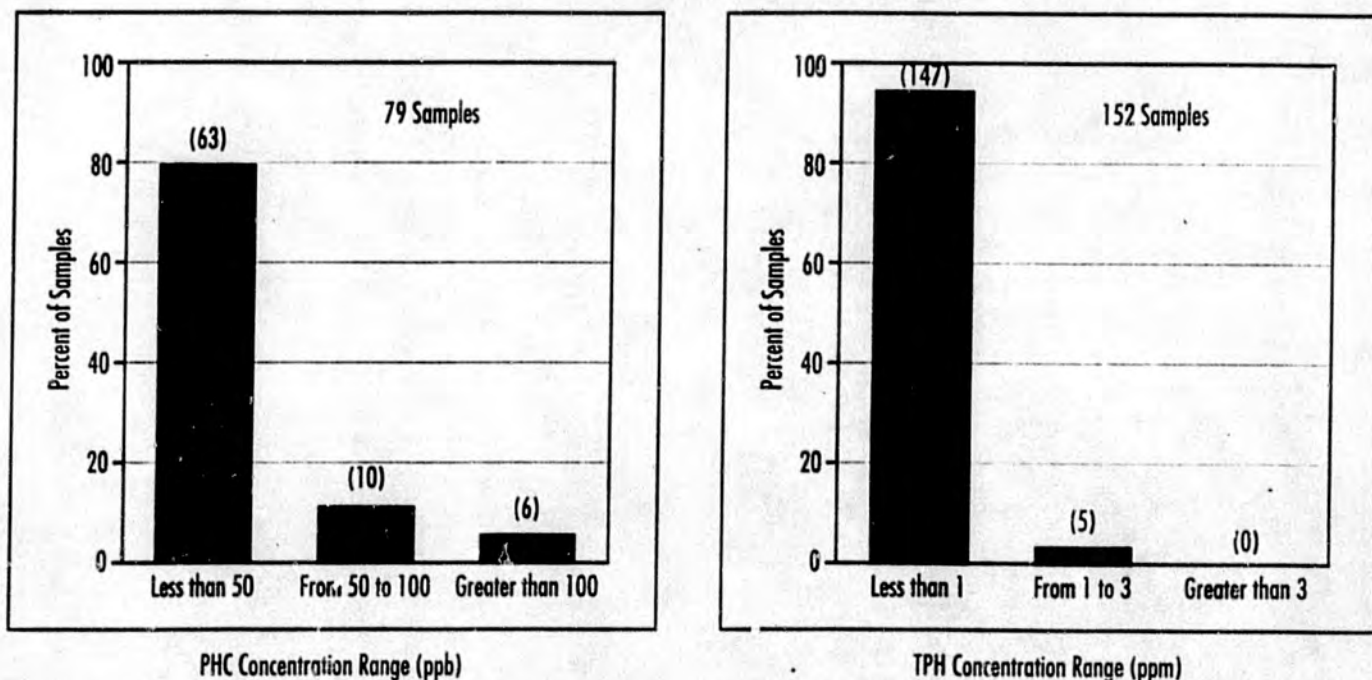


Figure A-2. Distributions of Petroleum Hydrocarbon (PHC) and Total Petroleum Hydrocarbon (TPH) Analyses (Nearshore Prince William Sound)

throughout Prince William Sound, with only a few samples (mostly surface samples) containing detectable concentrations of PHCs.

A total of 416 water samples (including 130

quality control samples) from the offshore water quality field surveys were analyzed for TPH. As indicated in Figure A-1, concentrations of TPH were below the method detection limit in 97

percent of the samples (276 of 286 water samples). Of the 10 remaining samples, 4 contained more than 3,000 ppb (3 ppm) TPH.

Water samples from the nearshore water quality field surveys, at both the shoreline monitoring sites (458 samples, including 156 quality control samples) and shoreline treatment monitoring sites (141 samples, including 62 quality control samples) were analyzed for PHC. One sample from a shoreline monitoring site contained 435 ppm PHC and obviously contained mousse; this sample was not included in the graphic data summary. As shown in Figure A-2, concentrations of PHCs were below the method detection limit of about 50 ppb in 82 percent (314 of 381 samples from both types of sites) of the samples. Twelve percent (44 samples) of the samples contained between 50 and 100 ppb PHCs, and 6 percent (23 samples) contained more than 100 ppb PHCs. The highest concentrations of PHCs in water samples (other than the samples containing substantial mousse or sheen material discussed above) from the shoreline monitoring and shoreline treatment sites were 1,000 and 300 ppb, respectively. Both samples were surface water samples.

A total of 285 water samples (including 65 quality control samples) were collected for TPH analysis during the shoreline monitoring surveys and shoreline treatment monitoring surveys. More than 96 percent of these samples (212 of 220 samples) contained less than 1,000 ppb (1 ppm) TPHs. The highest TPH concentration measured was 2,600 ppb (2.6 ppm).

Gulf of Alaska:

A total of 733 water samples (including 292 quality control samples) were collected for PHC analysis during the three Gulf of Alaska water quality studies. The ten samples containing mousse from the Kenai Peninsula were not included in the data summary (Figure A-3). Almost 92 percent (395 of 431 samples) of the water samples contained less than 50 ppb PHC (Figure A-3). Only 3 percent (13 samples) of the samples contained more than 100 ppb PHC. The highest PHC concentration measured in a water sample from the Gulf of Alaska (other than the samples from the Kenai shoreline containing mousse material discussed above) was 247 ppb. Six samples were analyzed for TPH during these studies; all resulted in nondetectable values.

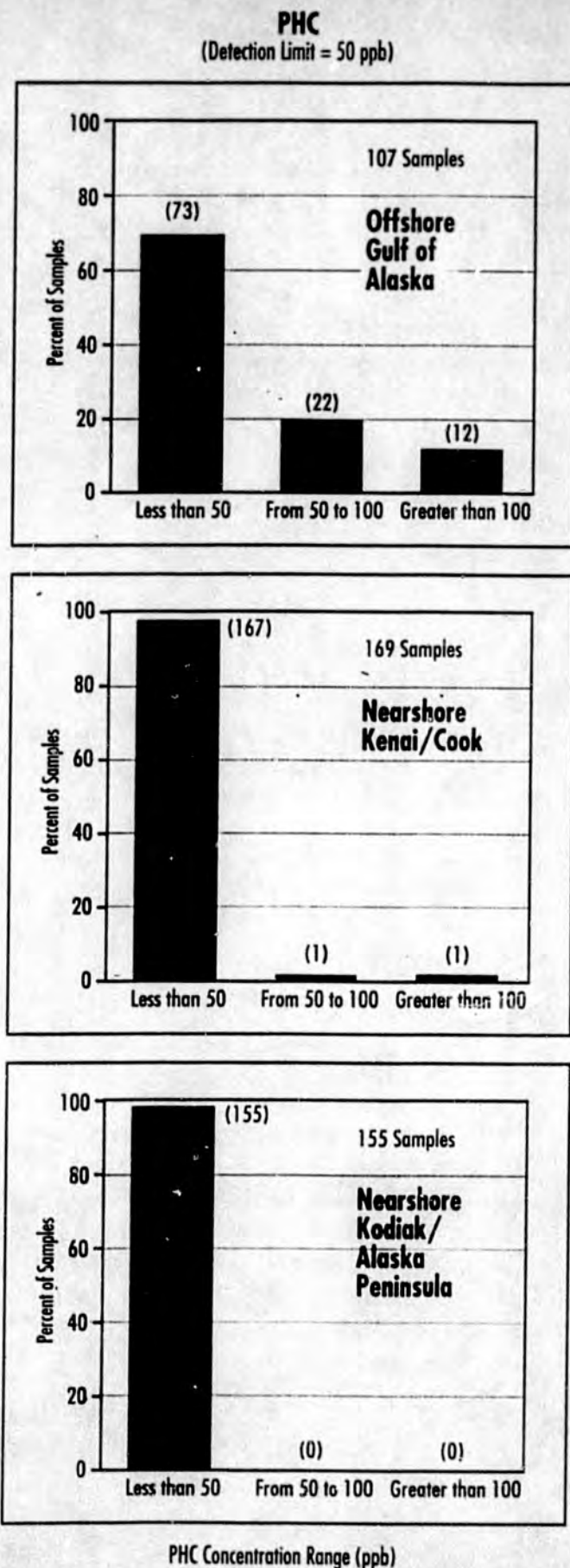


Figure A-3. Distributions of Petroleum Hydrocarbon (PHC) Analyses (Western Gulf of Alaska)

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ABOUT THE AUTHOR

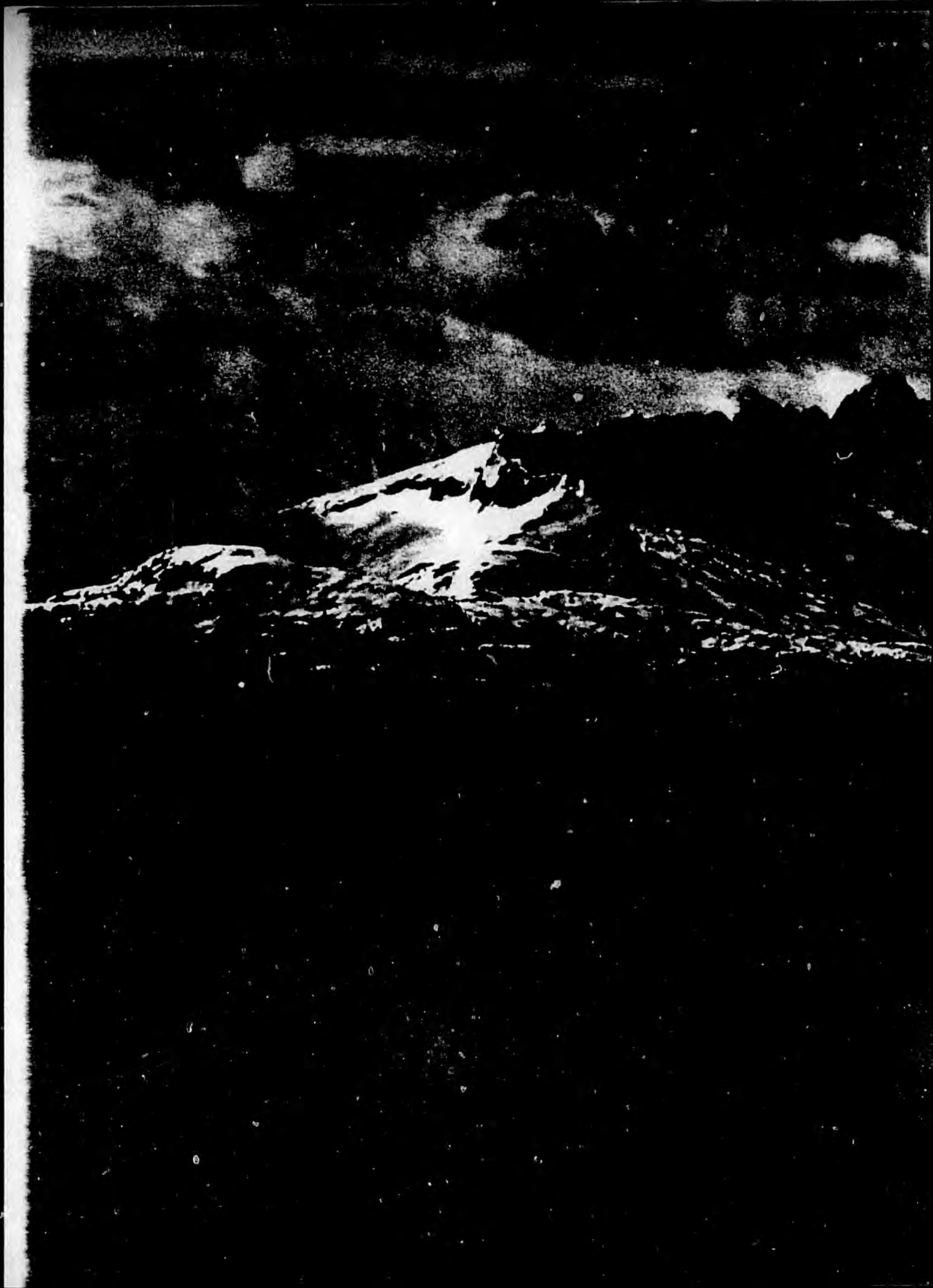


Dr. Jerry M. Neff, Senior Consultant with Arthur D. Little, is an internationally recognized authority on the fate and effects of pollutants in marine and freshwater environments. During the past 20 years he has participated in or managed more than 100 basic or

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Two Years After the Spill: Environmental Recovery in Prince William Sound and the Gulf of Alaska

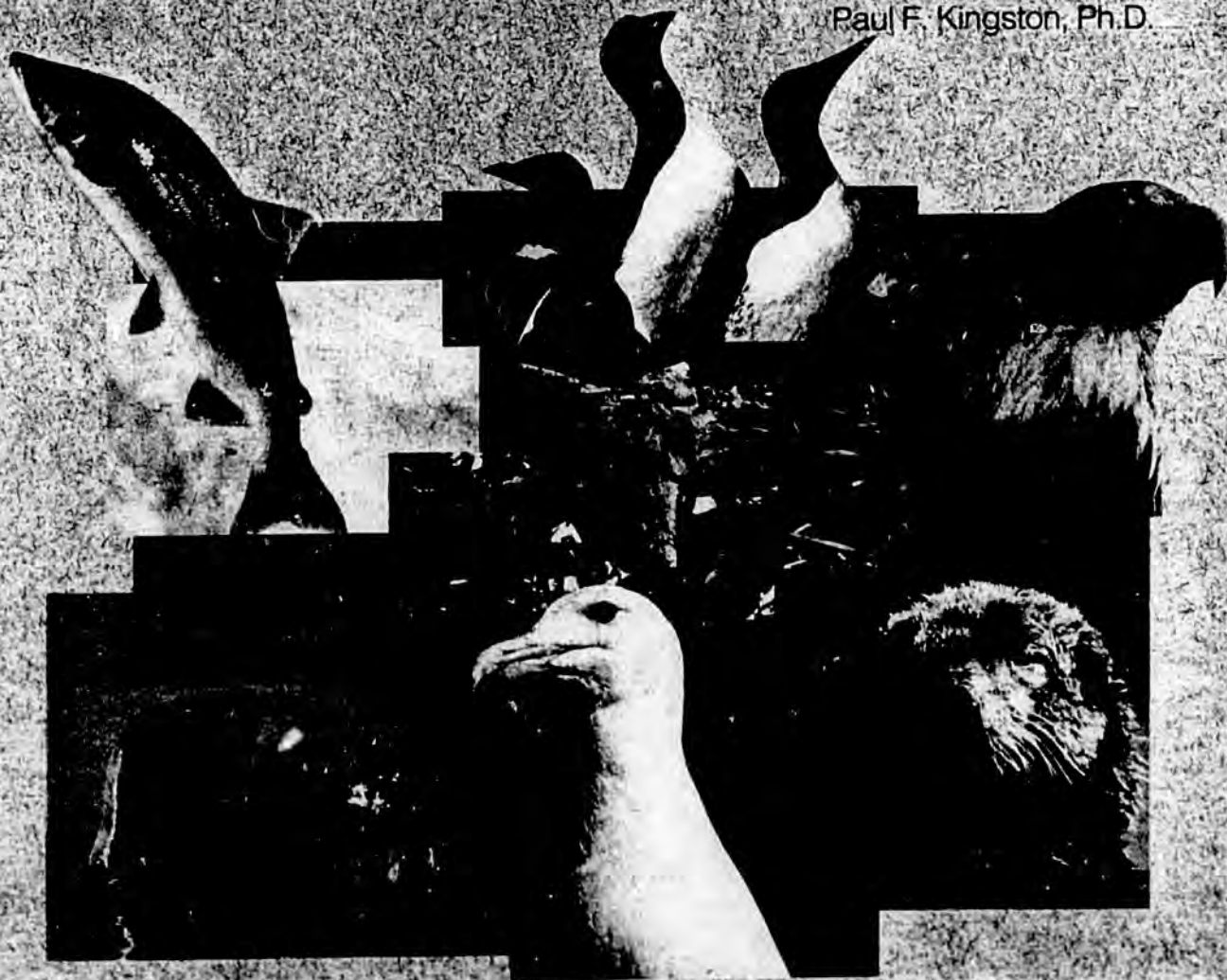
March 1991



Jennifer M. Baker, Ph.D.

Robert B. Clark, Ph.D.

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INTRODUCTION

A striking feature of the Valdez oil spill and its impact on the environment is the great disparity between public perceptions and fact. In 1989, the public learned from extensive media coverage that the oil spill had fouled beaches, killed seabirds and other sealife and disrupted fishing. As in other oil spills, natural recovery started quickly after the initial impact. The recovery, however, is not such dramatic news and has attracted much less media attention. In 1991, the public is therefore still left with its impression of "disaster," but is less aware that the affected areas are now well on the way to recovery.



The authors (from left to right: Dr. Paul Kingston, Dr. Robert Clark, and Dr. Jenifer Baker) during one of their 1990 visits to Prince William Sound, Alaska. All three have extensive international experience studying the impact of oil on the marine environment.

As James Mielke commented in his report to Congress for the Congressional Research Service, *Oil in the Ocean: The Short- and Long-Term Impacts of a Spill*, this is not a unique situation. Very much the same public misperception of "disaster" followed the wreck of the *Argo Merchant* on the Nantucket Shoals off the Massachusetts coast in 1976, when, in fact, minimal ecosystem damage was caused. The wreck of the *Amoco Cadiz* on the French coast in 1978 was the largest tanker oil spill on record (six times the size of the Valdez spill) and was claimed to be an ecological disaster. Although extensive damage was caused to the coastal environment, recovery in most areas was rapid.

The report we have written here is concerned with the recovery processes that have taken place in Prince William Sound and the Gulf of Alaska since the oil spill. Our observations and conclusions are based on factual evidence and run counter to some public perceptions, but they may help give reassurance that natural recovery is well underway and that the Valdez oil spill has no different implications than those relating to other cold water oil spills that have occurred around the world.

In December 1989, Exxon invited us to prepare a survey of the information in the published scientific literature on the recovery processes and rates of recovery of cold water marine environments following oil spills. At that time, there were no scientific publications relating to the Valdez oil spill and so it did not feature in our report.

Following the preparation of this technical report, we visited Prince

William Sound in the Spring (April, May) and Fall (September) of 1990 to form an impression of the recovery of oiled shores 12-18 months after the spill by "skilled eye" survey. Such surveys, using experienced observers to look for key features to monitor changes in the environment, are commonly used as part of gross environmental damage assessments. Our chief objectives were to discover if the recovery processes on the shores that had been impacted by oil were following the same pattern and were occurring at the same rate as those experienced in comparable situations following oil spills in other parts of the world.

We selected a variety of shore types for examination (including some that one of us, Dr. Baker, had studied in June 1989 before they were cleaned). They included shores that had been heavily oiled, lightly oiled or, for comparison, shores that had not been oiled at all; sheltered beaches and some exposed to severe wave action; and beaches that had been cleaned in various ways or, in one case, not cleaned.

In addition, we were able to form a view about the recovery potential of other elements in the marine environment that were at risk from the oil, based on our observations in the area, experience from previous oil spills, and reported events in the Sound during Summer 1990. We also addressed some of the concerns that have been expressed in public discussion or in the media (which we have followed closely since the event) or which we have encountered in discussions with local officials, other interested parties and members of the public.



Green Island (above) and Smith Island (below) in Prince William Sound, once heavily oiled, demonstrate the degree of recovery experienced by the shorelines in the area.



BACKGROUND TO OIL SPILLS

Oil spills, large and small, have happened in many parts of the world, and there is an enormous amount of scientific knowledge and information about the effects of oil on different types of marine environments, the recovery processes and rates of recovery. This experience has been reviewed and conclusions from it have been drawn several times by various distinguished bodies, including the U.S. National Academy of Sciences in 1975 and 1985, the U.K. Royal Commission on Environmental Pollution in 1981 and the U.N. Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) in 1982 and 1990. One of us, Dr. Clark, contributed to the first three of these reviews and was a founding member of GESAMP.

The consensus from all these overviews is that oil spills always have features in common and these need to be borne in mind when reading this report on the recovery of Prince William Sound following the 1989 oil spill. The features include:

- ▶ **Crude oil loses most of its toxicity within a few days of being spilled at sea.** Weathered oil is unlikely to poison plants or animals, but may smother them, and floating oil, whether still toxic or not, can be damaging to seabirds and sea otters if it contaminates their plumage or fur. In Prince William Sound and the Gulf of Alaska almost all of the oil reaching the shore had weathered at sea for many days or weeks.

Thin sheens may still occur after the bulk of the oil has either come ashore or dispersed at sea, but there is no evidence that they have any significant impact on marine ecosystems.

► **Recovery of the environment depends on the capacity of the unaffected plants and animals to replace the one-time immediate losses.** The speed of the recovery depends, first, on how quickly the damaging effects of the oil are removed, thus allowing recovery to start;



Occasional oil sheens may appear long after the bulk oil is removed. Sheens have little or no impact, as evidenced by the presence of beach plants.

second, on the numbers and species of survivors; and third, on how far the damaged area is from the nearest plants and other marine life available to recolonize it. No area in Prince William Sound was far from an undamaged area which acted as a reservoir for recolonization. Moreover, even on shores that were oiled there were many surviving plants and other marine life.

► **Once the bulk oil has been removed from the environment, either by human intervention or by natural processes, the mortality of marine organisms declines rapidly.** Most mortalities are immediate, but some organisms that have suffered sub-lethal damage may not recover and die after a short interval, or are unable to compete for long in the struggle for existence. Oil impacts are essentially short term. Concerns that damage which is not currently apparent will appear in future years is not supported by scientific evidence from any previous spills.

SURVEY OF SHORES

Following the spill, oiling of shores was an obvious concern because of threats to wildlife using the shores and because of fears that residual oil might be a long-term threat to marine life.

Clean-up operations in 1989 addressed these concerns and were more extensive and thorough than those after any previous oil spill in the world. The successful removal of bulk oil from beaches minimized long-term threats to wildlife, largely averted the formation of asphalt pavements and maximized the benefits of natural clean-up processes. These natural processes substantially reduced the amounts of residual oil during the period September 1989 to March 1990. In April 1990 we observed that shores in Prince William Sound and the Gulf of Alaska had a generally clean appearance but some weathered oil remained, mostly in sheltered inner bays or on upper shores. By September 1990 some of this remaining oil was more obvious, possibly resulting from the higher summer temperatures warming the oil, and allowing it to thin out and migrate through the beach material more easily. Another possibility is that this was the intended result of some types of beach cleaning which aim to expose sub-surface oil to promote its weathering.

In April 1990 we saw that recovery had begun and predicted normal growth and development would take place over the summer season. When we revisited the same beaches in September 1990, our predictions were

confirmed.

We examined the plant and animal life on shores because this intertidal flora and fauna is a good indicator of water quality. The early life stages—spores and larvae—of these organisms float in the surface waters of the sea before settling on the shore and they are particularly sensitive to toxic effects even at low levels of contamination. Furthermore, these shore plants and animals are important because most are low in the food chain and many fish, birds and mammals depend on them for food.

The summer settlement and growth of the organisms we saw was good biological evidence that the sea and the shores were clean enough for recovery to take place. Mussels, barnacles and rockweed that were abundant on the shores as newly settled juveniles in Spring had become established as young adult populations by the Fall. Such development had taken place even where there had been no clean-up or there was still residual oil on the shore. For example:



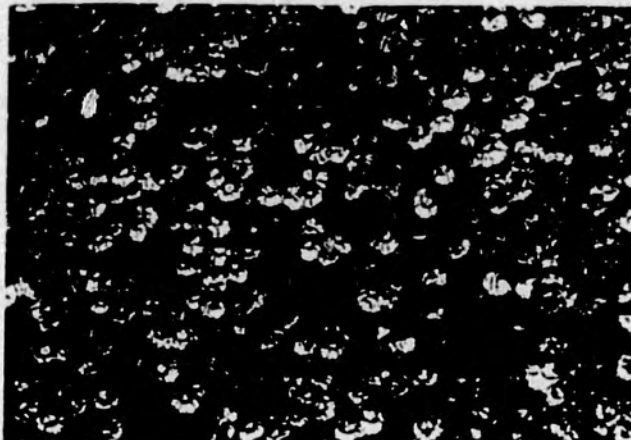
▲ April, 1990



► On the upper shore we found beach grasses in oily sediments sprouting in April and well grown in the Fall showing that there had been vigorous growth in the Summer.

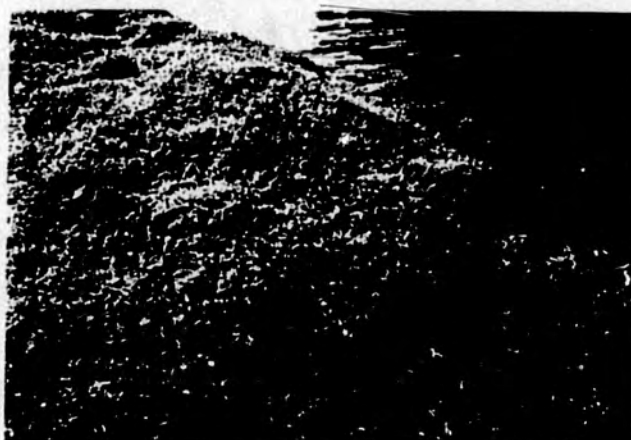
◀ September, 1990

► We saw that there had already been a good post-spill settlement of barnacles by April. In September there were well-established juvenile populations of barnacles on all shores together with



additional settlement of individuals that had taken place during the Summer.

► The rockweed sporelings (newly settled young plants) established in the Spring had developed into healthy stands of young adult plants.



► In the Spring, periwinkles (sea snails) were found under stones on several shores and frequently seen spawning. In September, rocks in most localities visited had large numbers of young individuals indicating a successful breeding season.





► On one beach on Seal Island, we discovered a lagoon in which oil was found under stones. Nevertheless, this lagoon had the richest and most varied marine fauna of any site we investigated. The same elements of

the fauna were present in April and September, a further indication that the presence of residual oil is not necessarily harmful to marine life.

► Mussels that had survived the initial oiling had been joined by newly settled juveniles.

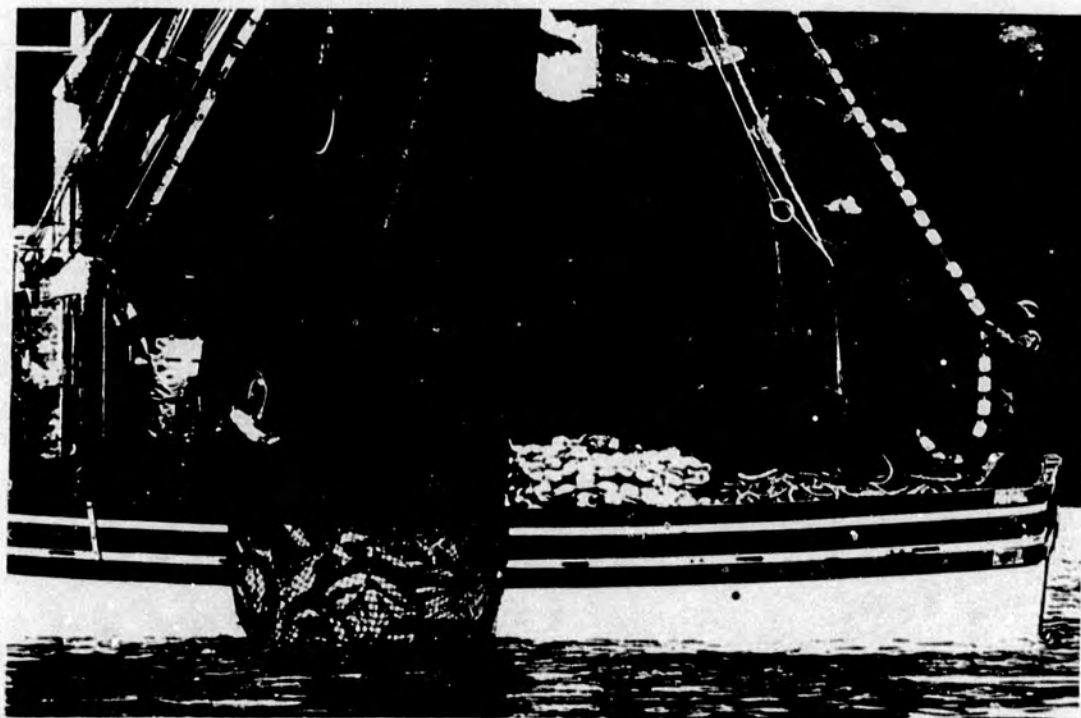
Our observations on the biological status of the shores suggest that the water quality in Prince William Sound is good. This is corroborated by the thorough study on water quality in Prince William Sound done for Battelle Ocean Sciences by Dr. Jerry Neff in which he shows that hydrocarbon levels in the water had returned to normal background levels by Summer 1989. Even at the highest hydrocarbon levels measured, concentrations were so low that they did not exceed the stringent drinking water standards of the U.S. Environmental Protection Agency.

COMMERCIAL FISHERIES

Commercial fishing is the second largest revenue-producing industry in Alaska, primarily involving salmon, herring and halibut.

Both wild and hatchery-reared salmon, as well as wild and pen-reared shellfish (oysters, shrimp and crabs) are harvested commercially. During the oil spill response, high priority was given to these hatcheries and farms as well as to protection and cleaning of the shores near salmon streams.

Except for such hatcheries and farms, observations at oil spills around the world consistently indicate that free-swimming, open-water fish are rarely at risk from oil spills. Fish swim away from floating oil and this behaviour



Prince William Sound fishermen enjoyed record-breaking pink salmon and herring harvests in 1990.

explains why there has never been a commercially important fish-kill of wild species following an oil spill. In fact, the only adult fish-kill on record following an oil spill was on the French coast when several tons of small rock-living fish (not commercial species) were killed at the site of the wreck of the *Amoco Cadiz*.

Fish eggs and larvae are more vulnerable and have often been killed in large numbers by floating oil. However, fish over-produce eggs on an enormous scale and the overwhelming majority of them die at an early stage, generally as food for predators. Even a heavy mortality from an oil spill has no detectable effect on the adult population which is exploited by a commercial fishery. This has been confirmed during the *Torrey Canyon* spill off southwest England and the *Argo Merchant* spill off Nantucket. In both cases a 90% mortality of fish eggs and larvae (pilchard and pollack, respectively) was observed in the affected area, but this had no impact on the local fishery.

Developmental abnormalities occur naturally in wild fish populations, and the frequency of these abnormalities is increased in populations chronically exposed to oil. These abnormal fish do not survive long in the struggle for existence. Such delayed mortality is likely to have an equally negligible impact on a commercial fishery as the immediate mortality following an oil spill.

The Valdez oil spill was no exception to the general experience. No fish-kills were confirmed in Prince William Sound as a result of the oil spill of 1989. There were, however, concerns about the possible impact of the

oil on the breeding cycle of two commercially important kinds of fish—salmon and herring.

Pink Salmon

Unlike the other four species of Pacific salmon, pink salmon have a two-year life cycle and spawn in summer in gravel at the mouth of creeks or in intertidal areas. They spend the following fall and winter developing, to emerge in the spring. They then spend a year offshore to return as spawning adults the following summer. In Spring 1989 when the oil reached the shore, young pink salmon were still in Prince William Sound close to the spawning



Pink salmon have a two-year life cycle. Adults that returned to the Sound to spawn in 1990 swam under oiled waters as juveniles in 1989.

areas, and the concern was that heavy losses of these younger salmon might have a serious impact on the number of fish returning to breed a year later in 1990. The fear was unfounded.

The 1990 pink salmon catch of these returning adults in Prince William Sound broke all records, with over 44 million fish caught compared to the previous record catch of 29 million. Even in September, when the peak of the spawning was over, we observed large numbers of spawning pink salmon at several beaches in Prince William Sound and the Gulf of Alaska.

Other Salmon

Unlike pink salmon, other salmon species spawn in several of the suitable rivers of Prince William Sound and the Gulf of Alaska. They breed upstream and the young fish eventually return to the open ocean for 4-5 years before returning to the rivers to breed. There were no reports of kills of salmon or their young in 1989 when oil was on the water, nor in 1990 when there was no longer oil on the water.

Herring

Herring congregate for spawning in enormous numbers in certain parts of Prince William Sound every April. The 1989 breeding season took place two weeks after the oil spill. There were fears that the spawning fish or their eggs would be damaged, and that the next year's and subsequent years' crops would be severely limited.

These fears fortunately appear to be groundless. We were present at the opening of the fishery in April 1990, one year after the spill. It was widely

reported that the fish were so abundant that the entire year's seine harvest quota was filled in just 20 minutes' fishing with a catch of 8,300 tons.

Halibut

This is another commercially important fish in the area. Halibut are bottom-living fish and there has been no indication that they were affected by the oil or that the commercial catch has suffered in any way.



Over 16,000 sea otters live in Prince William Sound and adjacent areas of the Gulf of Alaska.

SEA OTTERS

Sea Otters are appealing creatures and therefore have a high profile in the eyes of the general public. Although they were reduced to the verge of extinction by fur hunters in the last century, their numbers recovered in Alaska. However, a common public misperception is that they are still an endangered species in Alaska and thus there was great concern at the events following the Valdez spill.

Unlike other sea mammals, sea otters are vulnerable to oil on the sea primarily because if their fur becomes matted with oil, they rapidly lose body heat and die from hypothermia. The total mortality following the spill is unknown, but the best scientific estimate is that only a small fraction of the otter population in Prince William Sound died.

During our aerial surveys in April 1990 sea otters were frequently seen around many islands in Prince William Sound. Numerous other observers have reported frequent sightings of large numbers of otters including juveniles and pups in the Sound. It is apparent that there is a substantial surviving population from which the losses are being restored.

Research reported by Dr. James Estes in 1990 and carried out in Alaska, British Columbia and Washington state since the 1960s has shown that populations of sea otters throughout this region have increased at the very high rate of 17-20% per year until they reach a population limit set by the availability of their food.

Sea otters are abundant in Prince William Sound. With a potential for the population to grow at nearly 20% per year, we have concluded that whatever losses suffered in the oil spill are likely to be rapidly made good by natural reproduction.



Sea lions were not seriously at risk from the spill.

OTHER SEA MAMMALS

Scientific research suggests that whales, dolphins, seals and sea lions are not seriously at risk from oil spills. One of the reasons is that they rely on a layer of blubber under the skin, rather than fur, to insulate them from the cold. Whales and dolphins are hairless and even if they encounter floating oil, the oil does not stick to their bodies. Experiments with seals have shown that oil may stick to the fur but rapidly washes off.

In previous oil spills, there have been occasional reports of very small numbers of oiled seal or seal pup carcasses being found. These reports have generally not been well substantiated and it is not clear that oil was the cause of death. Similarly, whales do not appear to have been affected by oil spills. Gray whales migrated through the Santa Barbara Channel following the blowout of 1969, but there were no reports of casualties. The disappearance of some members of a resident pod of killer whales in Prince William Sound in 1989 and 1990 is therefore unexpected; it is not clear how they could have been affected by the oil, if, indeed, they were.



The abundance of nesting seabirds in the area and the size of their breeding colonies do not support fears of long-term adverse spill impacts.

SEABIRDS

Seabirds, particularly auks, are the most conspicuous casualties from oil spills. There are enormous seabird colonies in Prince William Sound and the Gulf of Alaska so even a small percentage of casualties means large numbers of birds were killed. The important question is how rapidly these losses will be restored by natural processes.

The dominant seabirds in the area are auks (murres, puffins, etc.) and gulls. Gulls are rarely affected by oil and at the time of the oil spill puffins had not yet returned to the Sound from their winter quarters farther south. Therefore, the concern centres on murres.

As in other cold water oil spills, the chief seabird casualties in Prince William Sound and the Gulf of Alaska were murres. There has been a good deal of concern that the damage caused to the murre population in Prince William Sound and the Gulf of Alaska would take decades to restore. Experience in other parts of the world suggests that this fear is not well founded.

Murres have an extremely low reproductive rate and several scientific studies have predicted, on theoretical grounds, that a substantial loss from a breeding colony would take 50 years or more to restore by natural growth. There were natural fears that this would apply to the colonies in the affected area, but this is most unlikely because when the theory has been tested by actually counting the size of breeding colonies in other areas affected by oil spills, it has proved to be wrong.

Murres, like many other seabirds, do not start breeding until they are 5-7 years old and, even then, do not necessarily breed every year. There is therefore a large reserve of non-breeding adults outside the breeding colonies, and this population of non-breeding adults replaces any losses from the breeding colonies. This accounts for the fact that breeding populations are not reduced even after natural disasters caused by severe weather or after oil spills. As an example of a natural disaster, over 100,000 murres died in the severe winter of 1971-72 in southwest Alaska.

Observations from the northeast Atlantic are relevant to Alaska because the same species is involved and because in this area there are long-term data available.

Tens and hundreds of thousands of murres have been killed in the northeast Atlantic *every year* since the 1920's by oil pollution from shipping in heavily trafficked sea lanes. Far from this causing a steady decline in populations, as the theory predicts, murres and other auks have all undergone a population explosion in the northeast Atlantic and are now at the limit of their food supply.

In the Gulf of Alaska the murre breeding season does not begin until May or June, but even in April 1990 we saw large numbers congregating near some of the larger breeding sites, including Barwell Island where the colony had reportedly suffered heavy losses in 1989. Many more murres were widely distributed throughout Prince William Sound and the Gulf of Alaska. To judge from experience in the northeast Atlantic, the size of the

breeding colonies in Prince William Sound and the Gulf of Alaska should be restored within a short time.

A remaining worry is that seabirds might continue to be killed by oil sheens on the water even though most of the oil was removed from the environment in 1989. During extensive overflights of Prince William Sound and parts of the Gulf of Alaska in April, May and September, 1990, we saw very few sheens. These were small, and their silvery colour indicated that they were very thin films of oil. There is no scientific evidence that these are harmful.

Sheens of this type are caused by boats discharging oily bilge water (as we observed on one occasion), by residual oil washing off beaches (as we observed off one beach), but are also produced naturally by algae. Seabirds are constantly exposed to sheens from natural or man-made sources, and spend most of their time, when they are not feeding, preening their feathers to keep them in a clean, waterproof condition.



BALD EAGLES

This noble bird is the national emblem of the United States, so feelings about it run high. It is an endangered species in the lower 48 states where it exists only in very small numbers. There was natural concern that some had been harmed by the oil.

Although there are very few bald eagles in the lower 48 states, they are not rare in Alaska. There are estimated to be 40,000 bald eagles in Alaska, probably the world's largest concentration of these birds. About 5,000 of them are in Prince William Sound.

During extensive aerial surveys of Prince William Sound and the Gulf of Alaska at the start of the 1990 breeding season, we observed bald eagles



Bald eagles are not endangered in Alaska, with more than 5,000 concentrated in the Prince William Sound area.

on prominent look-out trees at regular intervals around all forested coasts. At some sites we observed courtship displays and competition between male birds for territories.

Birds of prey have never before been victims of marine oil spills, but bald eagles are scavengers on the shoreline and presumably this activity resulted in some becoming oiled. Special teams captured 113 eagles in the most heavily oiled areas during the Summer of 1989. Evidence of oiling was noted on 35% of these 113 birds, and all but three of them were cleaned and eventually returned to the wild.

Eagles in the oiled areas had poor breeding success in 1989 with only about 200 young being produced in the Prince William Sound area. Scientific observers have attributed this to the disturbances caused by the clean-up activities and not the oil itself. In contrast, 1990 had a greatly reduced clean-up effort, and there was an active nest count of 1,031 with chicks being reared in previously oiled territories, according to the United States Fish and Wildlife Service.

The habits of these birds make it most likely that the breeding population will be quickly restored to its former level. Bald eagles do not breed until they are 5-6 years old and young non-breeding adult birds are widely distributed along rivers inland. There is competition for the breeding sites and the dominant birds occupy the best situations; any losses among the breeding population are filled by new recruits, at least by the next breeding season.

RESTORATION PROGRAMMES

There has been some public discussion about replanting and restocking damaged areas in Prince William Sound.

Such programmes to hasten biological recovery have occasionally been implemented elsewhere when there have been compelling reasons such as the prevention of coastal erosion. For example, a salt marsh on the French coast that had been severely damaged by oil-spill clean-up measures was replanted with appropriate vegetation, and eel grass beds destroyed by waste discharges in Florida and Australia have also been replanted. The reason for these extreme measures was because the salt marsh and eel grass beds were important in those areas as traps for sediment washed from the land, and without these barriers there would have been severe coastal erosion. That is why priority was given for their rehabilitation.

We have not seen damage requiring such measures in Prince William Sound and the Gulf of Alaska. Salt marshes in the area are very small so their significance in controlling coastal erosion is minimal. Moreover, in 1990 we saw that salt marsh plants, eel grass and beach grasses were growing well even on shores which had been heavily oiled in 1989 and still retained some residual oil.

Other shore organisms showed signs of rapid natural recovery. Many of the shores impacted in Prince William Sound were boulders or cobble stones exposed to severe wave action during storms (high energy beaches). Most of the plants and animals living on these shores are removed each year as a result of this natural turbulence. However, rapid recolonization takes place each season as part of the natural cycle of events in such hostile environments. There is an abundance of recolonizing organisms providing a reservoir from which shores damaged for any reason can be rapidly restored.

In conclusion, we saw nothing to indicate that further human intervention in the marine restoration process would be of any value.

CLEAN-UP

There have been continuing public discussions about whether further clean-up of remaining oil on the beaches in Prince William Sound and the Gulf of Alaska is necessary.

Whether or not further clean-up measures to remove this residual oil are justified largely depends on the human use a beach is put to. Our judgment is that where recovery of animal and plant life is already well established, the residual oil is obviously doing no harm and the organisms



With plant and animal life established, further intrusive clean-up could be counterproductive.

established on the shore will hasten the final removal and degradation of the oil residues. Further intrusive cleaning such as beach excavation and rock washing of beaches would kill the plants and animals already there and set the recovery process back to the beginning .

Experience has shown that after other oil spills, heavily-used tourist beaches may need to have most of the physically detectable oil removed. In that case, drastic measures are needed even at the expense of biological recovery. However, such beaches do not exist in Prince William Sound. Beaches need to be considered one by one, to decide whether there are special considerations which warrant further cleaning even though this could set back biological recovery.

CONCLUSIONS

There is a wealth of information about the recovery of cold water marine ecosystems following oil spills in various parts of the world. In all cases recovery events have been similar to those seen in Prince William Sound. If anything, because of the exceptionally thorough clean-up measures and natural cleaning processes, biological recovery has started sooner and proceeded further in Alaska than might have been anticipated.

There is no reason to suppose that the recovery process in the Prince William Sound oil spill are any different from those following other cold water oil spills around the world, many of them larger and more damaging. Although there have been a number of pessimistic forecasts in the media, there is nothing to suggest that there will be further delayed or long-term effects from the oil now that recovery is well underway.

These conclusions will not surprise any scientist experienced in the recovery of ecosystems following oil spills. In 1985, the U.S. National Academy of Science published an expert assessment of the threat posed by oil spills which is entirely consistent with our judgements, and there have been a number of similar expert reports published by distinguished international bodies to the same effect.

BIOGRAPHIES

Each author has had extensive international experience studying the impact of oil on the marine environment extending back over 20 years. Also, each has acted at various times as an independent scientific consultant to environmental bodies, government agencies or commercial organizations. The authors are all familiar with the scientific literature on oil spills and, indeed, have contributed to it significantly over the years.

Dr. Jenifer M. Baker

Dr. Baker is a marine biologist who conducts research on oil-pollution problems for conservation organizations, corporations, and government and United Nations organizations throughout the world. She is the former research director of the U.K. Field Studies Council, an independent environmental education and research organization. Her doctoral studies at the University of Wales involved research into the effects of oil and cleaning methods for salt marshes, and she later served as a staff member in the Botany Department of the University College, Swansea. She recently helped assess potential oil pollution problems on the great lakes of Africa for a conference organized by the International Association of Theoretical and Applied Limnology. A fellow of the British Institute of Biology and the Institute of Petroleum, Dr. Baker has published numerous papers in the scientific literature on the recovery of impacted shoreline ecosystems.

Dr. Robert B. Clark

*Dr. Clark, professor emeritus of zoology at the University of Newcastle upon Tyne, received his Ph.D. from the University of Glasgow and a D.Sc. from the University of London. He has served as director of the seabird research unit of the British Advisory Committee on Oil Pollution of the Sea (1969-75) and as director of the Natural Environment Research Council's Unit on Rocky Shore Surveillance (1980-87). He has served as member of the zoology faculty of the University of California at Berkeley and has worked with numerous national and international advisory bodies, including the United Nations Group of Experts on Scientific Aspects of Marine Pollution (of which he was a founding member) and the U.K. Royal Commission on Environmental Pollution. Dr. Clark is the author of the textbook *Marine Pollution* and is founder and editor of the monthly *Marine Pollution Bulletin*.*

Dr. Paul F. Kingston

Dr. Kingston is the Assistant Director of the U.K. Institute of Offshore Engineering and a former member of the marine biology faculty at Heriot-Watt University of Edinburgh, Scotland. He obtained his doctorate from the University of London and joined Heriot-Watt University in 1975 following a three-year research fellowship at the University of Newcastle upon Tyne.

*Dr. Kingston has worked in the field of marine environmental monitoring for over fifteen years. His experience covers a wide range of oil and non-oil related issues ranging from the Amoco Cadiz oil spill to the Channel Tunnel project on which he currently acts as Principal Marine Environmental Consultant. He has had extensive experience in assessing the impact of the North Sea industry on the marine environment and has worked on most major North Sea petroleum developments. His research interests centre on the structure and dynamics of seabed communities in relation to industrial and domestic environmental impacts. He has published extensively and currently serves as news editor of the *Marine Pollution Bulletin*.*



PRINTED ON RECYCLED PAPER

**Excavation and Rock Washing Treatment Technology
Net Environmental Benefit Analysis**

With Contributions From:

**Exxon Company, U.S.A.
National Oceanic and Atmospheric Administration
State of Alaska**

Compiled By:

**Hazard Materials Response Branch
National Oceanic and Atmospheric Admin.
7600 Sand Point Way, N.E.
Seattle, Washington 98115**

July, 1990



**U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration**

NATIONAL OCEAN SERVICE
OFFICE OF OCEANOGRAPHY AND MARINE ASSESSMENT
OCEAN ASSESSMENTS DIVISION
Hazardous Material Response Branch
7600 Sand Point Way N.E. - Bin C15700
Seattle, Washington 98115

July 9, 1990

RADM David Ciancaglini, USCG
Federal On-Scene Coordinator
601 West Fifth Street
Anchorage, AK 99501

Dear Admiral Ciancaglini:

Enclosed is the Net Environmental Benefit Analysis (NEBA) on excavation and rock washing, my concluding summary, and responses to that summary from the State of Alaska and Exxon. We were delayed somewhat in transmitting this material, awaiting the response from Alaska Department of Environmental Conservation.

It is important to note that the summary and conclusions represent my best judgement as Scientific Support Coordinator for the EXXON VALDEZ spill response. The interpretations therein should not be construed to reflect the opinion of the Agency in any broader context.

As you know, the NEBA studies have been relatively short term and specifically directed to the questions involved in this analysis. In accomplishing this task, we did not have the benefit of the studies being undertaken through the damage assessment programs of the Trustee Agencies or Exxon. Nothing in the attached material should be interpreted to imply an opinion on my part, or on the part of other contributors to this report, as to the extent of damage that may have occurred or may occur in the future as a result of the spill.

Sincerely,

John H. Robinson, Chief
Hazardous Materials Response Branch

Attachments



U.S. Department
of Transportation

United States
Coast Guard



Federal On Scene
Coordinator
U. S. Coast Guard

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601 W 5th Ave.
Suite 300
Anchorage, AK 99501
(907) 277-3833

16465
16 July 1990

Mr. Otto Harrison
General Manager
Exxon Alaska Operation
P. O. Box 240409
Anchorage, AK 99524-0409

Dear Mr. Harrison:

The Net Environmental Benefit Analysis (NEBA) Committee Report has been reviewed in its entirety. It is my understanding that the data contained in the report and submitted individually by NOAA, the State of Alaska and Exxon was included in toto for my consideration. Based on this data, I have determined that the benefits derived from the wide-scale use of the rock washer would be far outweighed by the detrimental effects caused by its usage. Although there is some disagreement regarding various conclusions in the report, there is sufficient basic information not in contention to support my decision. Therefore, as the Federal On Scene Coordinator, I will not authorize use of the rock washer. Essentially, the reasons for this decision are as follows:

A. With recolonization and a year's natural cleansing, the use of the technology would be detrimental to environmental recovery.

B. Considering the secondary environmental damage associated with the rock washer, damage to the lower intertidal zone and the mid intertidal zone habitats, and the unknown gain by using such an intrusive method, there are much better ways to improve the high human use and subsistence areas.

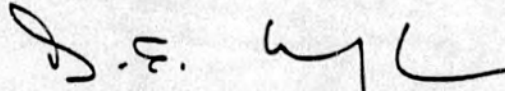
C. On those shorelines which still have significant subsurface oiling, the top 15cm of oiled sediment is of greatest concern. For those shorelines, other alternative treatment methods such as bioremediation, tilling, berm removal, etc. may be used to significantly reduce subsurface oil.

D. Based on the information contained in the NEBA report, the potential environmental hazard posed by the oil in its present state is far less than the certain ecological harm that would be incurred by rock washing. Biological recolonization is occurring, natural cleansing continues to remove oil, sheening is dramatically reduced, and commercial fisheries are taking place.

The process to develop the rock washer and study its effects on the environment is appropriate and consistent with the procedures employed prior to the use of other treatment technology used on this spill response.

A letter similar to this has been sent to ADEC and NOAA.

Sincerely,

A handwritten signature in dark ink, appearing to read 'D. E. C. W. L.', written in a cursive style.

D. E. CIANCAGLINI
Rear Admiral, U. S. Coast Guard
Federal On Scene Coordinator

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UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
OFFICE OF OCEANOGRAPHY AND MARINE ASSESSMENT
ROCKVILLE, MARYLAND 20852

JUL 17 1990

RADM David Clancaglini, USCG
Federal On-Scene Coordinator
601 W. Fifth Avenue, Suite 300
Anchorage, AK 99501

Dear Admiral Clancaglini:

I have personally reviewed the recent report of your Scientific Support Coordinator (SSC), Excavation and Rock Washing Treatment Technology: Net Environmental Benefit Analysis, and the summary and conclusions in John Robinson's July 5 cover memorandum. As Mr. Robinson stated in his July 9 transmittal to you, the report and its conclusions were based on the best information available to the report authors and the SSC at the time of their preparation.

The summary and conclusion of the report should not be interpreted as conclusive about the extent of comprehensive damages that have occurred and may continue to occur as a result of EXXON VALDEZ oil spill. In addition, the conclusions of the report should not be interpreted as precluding the need for restoration activities to enhance natural recovery processes. The Natural Resource Damage Assessment Program of the Federal and State of Alaska trustees must make those determinations.

The National Oceanic and Atmospheric Administration fully supports the conclusions reached in Mr. Robinson's memorandum of July 5 with respect to the specific question of the environmental benefits of washing rocks to remove subsurface oil.

Sincerely,

Charles N. Ehler
Director



***Excavation and Rock Washing Treatment Technology
Net Environmental Benefit Analysis***

With Contributions From:

***Exxon Company, U.S.A.
National Oceanic and Atmospheric Administration
State of Alaska***

Compiled By:



***Hazardous Materials Response Branch
National Oceanic and Atmospheric Administration
7600 Sand Point Way N.E.
Seattle, Washington 98115***

July 1990



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

NATIONAL OCEAN SERVICE
OFFICE OF OCEANOGRAPHY AND MARINE ASSESSMENT
OCEAN ASSESSMENTS DIVISION
Hazardous Material Response Branch
7600 Sand Point Way NE - Bin C15700
Seattle, Washington 98115

July 5, 1990

MEMORANDUM FOR:

RADM David Ciancaglini, USCG
Federal On-Scene Coordinator

FROM:

John H. Robinson, Chief *John H. Robinson*
Hazardous Materials Response Branch,
NOAA

On April 27, 1990, you requested that NOAA conduct a Net Environmental Benefit Analysis (NEBA) comparing the benefits of excavation and rock washing with the benefits of natural cleanup as augmented by the approved 1990 cleanup methodologies. A committee of technical experts from NOAA, the State of Alaska, and Exxon, was formed to investigate and attempt to reach some resolution of the issues involved.

The committee has worked diligently to define the environmental factors important to the analysis, research the scientific literature to gain insight from past spills, and undertake field programs to obtain additional data where necessary.

The NEBA committee produced the attached report following a mutually agreed-upon outline and technical approach. All members of the committee were provided the opportunity to comment on a draft of the final report and the authors of each section were urged to consider committee member comments in their final manuscripts. The opportunity to append other viewpoints was provided. NOAA then prepared a summary of the report which is included as an attachment to this memorandum. The summary was forwarded to the State of Alaska and Exxon for review and comment; comments received were considered in the final draft.

Many key technical issues surrounding the analysis were partially resolved in the course of this undertaking and on some topics the range of disagreement was substantially narrowed. In accord with your instructions, NOAA attempted to reach a consensus on the question and



reserved our position on the issue until it became clear that the major parties to the matter would be unable to reach agreement on the key issues.

Given the disagreement between the State of Alaska and Exxon on the conclusion of the analysis, we offer our opinion that there is no net environmental benefit to be gained from shoreline excavation and washing — in fact we believe that this technology has the potential of aggravating the injury to the environment caused by the oil spill.

We believe that the data gathered in the process of this analysis support the contention that deeply buried subsurface oil (i.e., oil beyond the reach of near-term bioremediation and other less-intrusive cleanup methods) poses little risk of causing further significant environmental injury. This finding is borne out by the following:

- There is evidence of a substantial reduction (up to 90%) in the top 20 cm of the shoreline since September of 1989. Subsurface oil should continue to be reduced gradually as fall and winter storms scour the coast.
- There is evidence that the frequency and magnitude of sheens have decreased significantly over the past several months and chemical changes in the subsurface oil have rendered it much less capable of sheening. Commercial fisheries closures attributed to sheening are infrequent.
- There is evidence that recolonization of biological communities is proceeding in candidate areas for rock washing. There is no evidence that subsurface oil is causing a serious impact to intertidal or subtidal organisms, either by direct contact or by indirect contact through adverse effects on nearshore water quality.
- There is evidence that the toxicity of subsurface oil is continuing to decline, primarily as a result of microbial degradation.

The case against excavation and rock washing is further accentuated by a review of the negative impacts of that technology:

- Excavation would alter the natural structure and profile of the shoreline, and require one to three years for a return to equilibrium.
- Excavation would eliminate virtually all plant and animal life indigenous to the mid- and upper-intertidal zone and may cause a

significant adverse effect in the highly productive lower intertidal zone. Biological recovery of the shoreline following excavation would require four to eight years compared with two to six years if left to natural processes.

- Excavation would cause numerous large-scale secondary impacts associated with fuel consumption, incidental spills, noise, air pollution, siltation, possible archaeological disturbance, and human intrusion into the affected shoreline areas.

We believe that the only benefit to be derived through excavation and rock washing is the predictability that oil would be promptly removed from the subsurface environment, eliminating the potential for future contamination that might disrupt human use of the shoreline and nearshore waters. This potential benefit, in our opinion, is certainly far outweighed by the ecological disruptions that would be result from use of this technology.

We believe that the conclusions reached through this analysis strongly support natural cleanup processes and continuation of the approved 1990 cleanup program.

Attachments

SUMMARY

A technical committee was formed in May 1990 to investigate the environmental tradeoffs associated with excavating and washing oiled sediments remaining deeply buried along some sections of the Alaskan shoreline affected by the EXXON VALDEZ oil spill. The committee, comprised of Exxon, NOAA, and State of Alaska scientists, was charged with conducting a Net Environmental Benefit Analysis (NEBA) related to the advisability of excavation/washing in comparison to natural cleansing and application of treatment protocols approved by the Federal On-Scene Coordinator for use in 1990.

The NEBA committee selected two shoreline segments, Sleepy Bay on the north coast of Latouche Island and Point Helen on the southeast coast of Knight Island, as candidate locations to pursue field studies associated with the analysis.

The committee collectively outlined the range of environmental issues important to the analysis. The benefits and negative impacts of excavation and rock washing were researched in some detail, using both site-specific data from the candidate beaches and published studies on the fate and effect of oil and the impacts of physical disturbances to the shoreline. The results of these analyses can be summarized as follows.

How much oil is buried at what depths along the most severely affected sections of the coast? What are the prospects for removal by natural processes?

During the March/April 1990 shoreline assessment, 212 of the 1,134 shoreline segments surveyed had subsurface oil deposits thicker than 15cm and buried deeper than 15cm. Of 5,071 pits dug in the assessment, only 279 contained oil that had penetrated greater than 30cm, with 25 that had oil penetration greater than 60cm. The deepest occurrences of subsurface oil were found on coarse-grained beaches (boulder/cobble/pebble) along exposed shorelines.

NOAA studies at 18 stations in Prince William Sound over the six-month period from September 1989 to March 1990 indicated that, on the exposed shoreline segments most likely to be amenable to excavation, sediment reworking resulted in the removal of oil from the top 10-20 cm of

surface sediments. Data taken from Sleepy Bay and Point Helen reflected a 90% oil reduction in the top 30cm, but no discernible trend in oil reduction was evident below this depth. Exxon's winter monitoring study at 18 sites in Prince William Sound concluded that the concentration of total petroleum hydrocarbons (TPH) in subsurface sediments (generally >10cm) declined by 88% over the same period.

Using various survey methodologies, the estimated amount of oil remaining in subsurface sediments at Sleepy Bay, one of the candidate sites for excavation, was:

Gallons/meter of Shoreline	No. of Samples	Source
9.9	43	NOAA Oct-Feb Survey
5.0	13	Exxon Mar Survey
6.1	11	Exxon Jun Survey

Perhaps of more importance than the quantity of subsurface oil is the rate of natural removal which may be expected over the next few years. There have been numerous studies of previous spills in which the persistence of stranded oil has been surveyed. However, there are many factors specific to Prince William Sound that might alter the extrapolation of oil persistence curves from other spills to the EXXON VALDEZ. The factors that may speed natural removal processes in Alaska are:

- 1) Flocculation, the process by which fine-grained sediments adhere to the subsurface oil and make the oil less sticky and more biologically available.
- 2) Enhanced biodegradation, both naturally occurring and stimulated by the addition of nutrients.
- 3) Removal of surface oil during the 1989 treatment, which limited the formation of asphalt pavements.

The factors that may slow natural removal rates in Alaska are:

- 1) The relatively low wave energies relative to the grain size of shoreline sediments.
- 2) The initial high degree of contamination of some shoreline segments.

Oil removal is expected to be most pronounced early in the recovery period; this expectation is clearly being borne out by data gathered thus far through the various monitoring programs. NOAA estimates that virtually all of the oil buried in gravel shorelines should be removed, given no further treatment, in the periods of time indicated below:

Sheltered parts of Prince William Sound	10+ years
Sheltered outer Kenai	3-5 years
Exposed parts of Prince William Sound	2-4 years
Exposed outer Kenai	1-2 years

At what rate is subsurface oil being weathered?

Samples of subsurface oil were collected by NOAA from the two NEBA study areas and analyzed by gas chromatograph/mass spectrometry (GC/MS) to determine both chemical composition and weathering trends. Most of the subsurface oil in these samples was moderately to heavily weathered and altered significantly in both physical and chemical properties from the original state. Physically, the oil had become more viscous, less sticky, and would not readily sheen. Chemically, the oil had lost many of the light- to moderate-weight polynuclear aromatic hydrocarbons (PAHs), components which are of greatest toxicity to aquatic organisms. For example, the naphthalenes and phenanthrenes had been reduced by more than a factor of 100 when compared with fresh EXXON VALDEZ oil. Analysis of the saturate fraction of this subsurface oil showed strong evidence that microbial degradation had occurred. Overall, the subsurface oil had decreased in both concentration and toxicity and showed evidence of significant microbial degradation.

Will subsurface oil become exposed by wave action?

It is likely that there will be further removal of subsurface oil by wave action and shoreline erosion; however, these processes are most likely to

occur in the winter when sediment abrasion and thus natural cleaning of the surface is at a maximum. There is no general agreement as to the rate at which the oiled subsurface sediments would be exposed by these processes. Larger cobbles exposed during severe winter storms may remain with some surface oil contamination; the smaller sand, granules, and pebbles would rapidly be cleaned.

To what degree is water within the beach being contaminated by subsurface oil and thus exposing organisms to toxic hydrocarbon compounds?

Water within the beach ("pore water") comes in contact with subsurface oil as it moves through the interstitial space among oiled sediment particles. The prospect that pore water may become contaminated was investigated by the committee.

An Exxon mathematical model was used to predict the concentration of PAHs in pore water, which contacts subsurface oil deposits, and the rate at which tidal flushing would leach the water-soluble fractions of the oil. Using data on concentrations of PAHs in sediments collected in March 1990, Exxon predicted that concentrations of total PAHs in pore water would be generally below 20 ppb. These model results were confirmed by Exxon analyses of field samples of pore water collected in March at eleven sites in Prince William Sound. Only one sample contained PAH levels greater than 10 ppb and only three reflected levels greater than 1 ppb. Two of the three highest values were for samples collected from Sleepy Bay. All observed levels of pore water contamination are below concentrations known to be acutely toxic to marine organisms.

An additional twelve water samples were collected by NOAA at the sediment/water interface during falling tides from Sleepy Bay in May 1990. Total PAH concentrations in these samples were all less than 1 ppb. The rapid dilution of the pore water as it mixes with clean interstitial and shallow subtidal waters should result in PAH concentrations that pose little or no toxic hazard to marine organisms on the lower shore and in subtidal waters.

To what extent can sheens be produced by subsurface oil? If such sheens are produced, what adverse effects can be anticipated?

The committee investigated the frequency, magnitude, composition, and effect of oil sheens likely to originate from subsurface oil. Observations by ADEC and Exxon show a declining trend in both sheen frequency and volume throughout Prince William Sound. The downward trend in Exxon data is more pronounced, possibly due to the elimination of non-Prudhoe Bay crude sheens from the data set. On a weekly basis, the volume of sheens from EXXON VALDEZ oil is now well below the present level of petroleum hydrocarbons introduced to surface water of Prince William Sound from other sources (vessel traffic, combustion, natural organics, etc.).

NOAA chemical analysis indicates that the natural weathering of subsurface oil has rendered the oil both less toxic and much less capable of producing sheen. As long as the oil remains physically stable in the shoreline, sheen frequency should be minimal. A temporary increase in sheening would likely be produced either by excavation or by intense winter storms. Sheens produced by excavation could be expected to be controlled in light to moderate weather conditions. While control of storm-induced sheens is unlikely, the range and effect of such sheens would be limited by natural dispersion during the storm event. NOAA studies in 1989 indicated that only in unusual weather conditions would convergence zones have the potential to concentrate free-floating oil into popweed windrows to the extent fishing gear might be contaminated. The threat of exposure to birds feeding at these windrows is likely to be small as exemplified by the lack of reports of oiled marine birds this year.

In summary, subsurface oil is relatively stabilized and insulated from exposure to vulnerable resources through sheening. Adverse effects on birds, fish, wildlife habitat, or human uses are not expected to originate from sheens produced by subsurface oil.

What is the near- and long-term fate of subsurface oil?

Subsurface oil that persists in the shoreline will eventually be degraded by indigenous bacteria. However, prior to the complete microbial breakdown of oil buried deep within the shoreline, other processes may be important in controlling the intermediate distribution and fate of the oil.

Flocculation is one process that has been proposed by Exxon as being an important mechanism for enhanced natural removal and dispersal of subsurface oil. The flocculation process has been demonstrated in laboratory studies, and in the field some subsurface oil appears to have taken on a more weathered, smeary texture indicative of floc formation. However, the rate of flocculation and its relative importance, particularly in the removal of heavily oiled subsurface sediments, is not known.

There is some concern that the fine-grained fraction of oiled subsurface sediments may be exposed by erosion and deposited in the nearshore subtidal environment. Since there are few data available to evaluate this potential risk, a diving survey was conducted by ADEC in June 1990 to collect subtidal sediments along a transect out to 100m off both Point Helen and Sleepy Bay. Total PAHs in these subtidal sediments were 0.1-9 ppb off Point Helen and 1-130 ppb off Sleepy Bay. This limited sampling would indicate that deposition of oiled sediments, derived from either subsurface or surface sources, may be minimal.

What are the potential effects of rock excavation on the shoreline substrate?

There is great variability in sediment grain size and shoreline exposure in Prince William Sound, and therefore the effects of excavation and rock washing on the structure of the intertidal zone would vary considerably from location to location. Shoreline segments that contain high concentrations of subsurface oil are also generally exposed to moderate or high wave energy. The upper part of the intertidal zone in these locations is affected by the erosion and deposition of high-tide berms, as shown through analysis of data obtained during the Exxon, NOAA, and ADEC winter monitoring programs. The middle and lower intertidal zones are less affected, particularly if a cobble/boulder armor is present, such as on Point Helen, one of the candidate sites for rock washing.

Using data from the winter monitoring programs and case histories from other studies, it is predicted that, if the material were removed from the upper one-third of the beach and replaced in approximately the same position from which it was taken, the upper berms at Point Helen would reestablish themselves after two or three medium-sized storms. The re-armoring process in the middle and lower part of the shoreline would require a few more storms, possibly covering a period of one to three years.

For Sleepy Bay, which is more sheltered but also is composed of finer-grained sediments, the upper surface sediment resorting should occur in less than one year. However, because the middle portion of the beach changes more slowly, complete reestablishment of the original profile and sediment resorting may require up to three years, though it may take place sooner. Recolonization by intertidal organisms would be delayed during these periods of sediment restabilization.

Loss of fines is not expected to be of concern, mainly because of the relatively small percent of sand-sized materials in the upper zone on most beaches in Prince William Sound. Because the sand exists primarily as a matrix to the already fixed framework of the beach, there should be no impact of its potential loss on beach morphology or erosion. There were concerns that the loss of sand might change the hydraulics of the beach, but the magnitude or consequences of this impact are unknown.

What are the effects of subsurface oil and excavation on the recolonization by intertidal communities?

In the areas where excavation is being considered, the intertidal zone can be divided into three subzones on the basis of the distribution of biological communities. The upper intertidal zone, generally the location of the highest concentrations of subsurface oil, is normally not inhabited by a very rich biological community because of relative dryness, sediment mobility, and lack of food.

The middle intertidal zone contains a more rich and diverse biological community. Observations made this spring and summer indicate that these communities are recovering from the oil and treatment activities. Oil concentrations of the surface sediments in this zone are generally low and, as discussed earlier, toxic impacts from the discharge of groundwater through oil-contaminated sediments across this zone are not expected to be significant. Because most of the plants and animals in this zone live in the top 10-15cm, there is no pathway of exposure to subsurface oil other than oil exposed during erosional events. To the extent the oil remains buried, it poses no serious risk to intertidal communities in this zone.

The lowermost intertidal zone has the greatest biomass and species diversity. In most cases, this zone is showing evidence of recovery and only

very low concentrations of oil occur in the surface sediments. The lower intertidal zone would be least impacted by the residual subsurface oil.

With the information available on the likely zone of disturbance by excavation and rock washing, it is assumed that few organisms in the upper and middle intertidal zones would survive. There may also be impacts to these zones resulting from the traffic of equipment and people on the shoreline. It is likely that these surface impacts would extend to some degree into the relatively rich lower intertidal communities.

NOAA estimates that three to five years would be required for biological recolonization after the shoreline stabilizes. Adding one to three years for stabilization, the total recovery period after excavation is estimated to be four to eight years. If excavation does not occur, NOAA estimates recolonization will occur in two to five years at Point Helen and three to six years post-spill at Sleepy Bay.

What would be the secondary impacts from excavation and rock washing?

Increased sediment loading in the water column would be unavoidable during excavation and replacement. Coarse material would settle out readily, although it is likely that oiled silts and clays would settle slowly and might be transported along the beach by tidal currents.

Secondary spills of fuel and process water were estimated using the spill rate of cleanup activities in 1989. Assuming that four or five rock washing units were active for a two-month period, an estimated eight to ten fuel spills would occur.

Excavation and rock washing would disturb wildlife with work activity and noise for six weeks or longer in each work area. Sources of disturbance include personnel, vessels, equipment, and aircraft. Traffic in the intertidal area may further affect the recolonization process.

Exxon estimates that excavation and rock washing at Sleepy Bay would generate 12,000 gallons of skimmed oil/water mixture, 168,000 gallons of wastewater, 500,000 gallons of sludge waste, and 300,000 pounds of air emissions. Fuel consumption is estimated at 400,000 gallons.

What would be the impacts on human use of the shoreline and nearshore waters should subsurface oil not be removed? What would be the related effects of excavation/rock washing?

The State of Alaska indicates that any of the shoreline segments which are candidates for excavation and rock washing are in areas of moderate to high human use. These areas are used throughout the year for recreation, subsistence and commercial fishing, and are of significant cultural importance. Subsurface oil has some capacity to pose an episodic threat to these uses of the shoreline and nearshore waters.

Although sheens are declining in Prince William Sound, and the relationship between sheens and subsurface oil is tenuous in non-storm conditions, commercial fishing in the immediate vicinity could be affected in the event sheening does occur. Episodic releases of subsurface oil may contaminate subsistence fisheries, interfere with shore-based commercial and recreational fishing, and impair use of the shoreline for recreation. Large amounts of subsurface oil can impact recreation and subsistence users who dig fire pits in the upper intertidal zone.

Excavation/rock washing is one of the most predictable means of assuring that oil is removed from the environment rather than remaining as a potential source for episodic exposure during winter storms. The expected impacts of the excavation and cleaning process include potential for temporary sheening or resuspension of oiled particulates, creation of silt plumes, and disturbance by equipment and personnel. These impacts can be mitigated by proper containment of sheens and timing of operations to minimize impacts to resources and users. Recreational and some subsistence uses could resume soon after the treatment process. Other subsistence activities would be delayed four to eight years until natural recolonization of intertidal biota occurred.

FOREWORD

This report was only possible through the dedicated efforts of many individuals who worked extraordinarily long hours for several weeks in meeting the stringent deadlines associated with its production. The authors especially wish to thank Lori Harris of NOAA for her outstanding efforts in compiling both the draft and final manuscripts.

TABLE OF CONTENTS

	<u>Page</u>
I. Definition of Study	1
A. Objective	1
<i>Jacqueline Michel</i>	
1. Statement of the Problem.....	1
2. General Approach.....	2
B. Description of Excavation Rock Washing	3
<i>N.K. Springer, J. J. Kichner, B. A. Twidwell</i>	
1. General Technology.....	3
2. Process Flow Diagram.....	4
3. Overview of Process Capabilities.....	4
4. Operational Concepts and Logistic Considerations.....	6
5. Expected Process and Ancillary Equipment.....	10
6. Operations.....	12
C. Description of Candidate Beaches	16
1. Selection Criteria.....	16
<i>Jacqueline Michel</i>	
2. Geomorphology.....	19
<i>Miles O. Hayes, Ed Owens, and Eugene Pavia</i>	
3. Sediment Oil Content and Composition of Candidate Beaches	39
<i>Jacqueline Michel and Charles Henry</i>	
4. Pore Water Chemistry.....	66
<i>Jerry Neff and Charles Henry</i>	
5. Beach Hydraulics.....	78
<i>Ed Owens</i>	
6. Treatment Histories.....	79
<i>Eugene Pavia</i>	
7. Biological Conditions	80
<i>Ed Long, Charles Cairncross, Jerry Neff, Sam Stoker</i>	
8. Human Uses.....	92
<i>William Copeland</i>	
II. Environmental Considerations.....	94
A. Base Case: Approved 1990 Treatments and Natural Cleansing.....	94
1. Trends in Oil Residue Content of Subsurface Sediment Samples From Prince William Sound.....	94
<i>Hans Jahns</i>	

II. Environmental Considerations, cont.

Page

2. Trends in Natural Removal Rates of Subsurface Oil.....	101
<i>Jacqueline Michel, Miles O. Hayes, Charles Henry</i>	
3. Effects of Subsurface Oil Residues and Projections of Recolonization	108
<i>Ed Long</i>	
4. Sheening—Frequency, Volumes, Persistence.....	123
<i>Gerald Schimke, Jerry Neff, Charles Henry, Marshal Kendziorek, Ed Meggert</i>	
5. Human Use Considerations Under Continued Natural Cleansing and Approved 1990 Treatments.....	145
<i>William Copeland</i>	
6. Ultimate Disposition of Subsurface Oil	146
<i>Jerry Neff, Eugene Pavia, Charles Henry</i>	
B. Excavation/Rock Washing.....	160
1. Effects on Beach Substrate	160
<i>Miles O. Hayes, Ed Owens, Eugene Pavia</i>	
2. Effects on Intertidal Biota and Projections of Recolonization.....	163
<i>Gary Shigenaka, Ed Long, Mark Kuwada, Jerry Neff</i>	
3. Water Quality.....	178
<i>Eugene Pavia and Ed Meggert</i>	
4. Impacts on Human Interests.....	179
<i>Mark Kuwada and William Copeland</i>	
5. Impacts on Cultural Resources	179
<i>William Copeland</i>	
6. Impacts of Waste Handling and Disposal	180
<i>John Wilkinson</i>	
III. Summary.....	183
<i>Jacqueline Michel and John H. Robinson</i>	
References	192
Appendix A: Case Histories.....	A-1
<i>Ed Long, Gary Shigenaka, Charles Cairncross</i>	

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LIST OF ABBREVIATIONS

ADEC	Alaska Department of Environmental Conservation
ADF&G	Alaska Department of Fish and Game
ADNR	Alaska Department of Natural Resources
cm	centimeter
GC/MS	gas chromatograph/mass spectrometer
km	kilometers
K _{ow}	octanol/water partition coefficient
mg/kg	milligram per kilogram
µg/l	micrograms per liter
m	meter
mm	millimeter
MLLW	mean lower low water
NEBA	Net Environmental Benefit Analysis
NOAA	National Oceanic and Atmospheric Administration
ng/l	nanograms per liter
ng/mL	nanograms per milliliter
PAH	polynuclear aromatic hydrocarbons
PCB	polychlorinated biphenyls
ppb	parts per billion
ppm	parts per million
SCAT	Shoreline Cleanup Assessment Team
SSAT	Spring Shoreline Assessment Team
TPH	total petroleum hydrocarbons

LIST OF FIGURES

	<u>Page</u>
I-1 Preliminary process diagram (KCM, Inc. and Northwest Enviro Service, 1990)	5
I-2 Beach excavation rock washing project (not to scale).....	13
I-3 Location map showing the two candidate beaches at Sleepy Bay and Point Helen.....	17
I-4 Beach sketch of NOAA's station N-1 at Point Helen at low tide on 24 May 1990. Note presence of storm and spring-tide berms near high-water mark and bedrock outcrop in lower portion of the profile. Buried oil occurs on the upper one-fourth of the beach.....	20
I-5 Beach profile at NOAA's station N-1 at Point Helen that was measured at low tide on 24 May 1990. The beach is classified morphologically into three zones: (1) <u>high-tide berms</u> , an area subject to fluctuations of berm levels during storms and spring tides; (2) <u>stable central ramp</u> , bypass zone with an armor of cobbles and boulders; and (3) <u>low-tide bars</u> , boulder/cobble zone that sometimes contains gravel swash bars.....	21
I-6 Plot of 25 estimates of grain size of surface sediments along NOAA's profile N-1 on 24 May 1990.....	23
I-7 Distribution of grain size of surface sediments adjacent to NOAA's profile N-1 on 24 May 1990. Dots along profile line indicate points where grain size estimates are made	24
I-8 Description of three trenches dug on NOAA's profile N-1 on 24 May 1990 (see Figures I-4, I-5, and I-7 for location). Note tendency for upper units to be somewhat coarser grained than lower units. Also note that the upper sediments in trenches A and B are relatively free of oil as a result of wave action during the non-summer months of 1989 and 1990.....	25
I-9 Plot of grain size estimates for sediments from the trenches described in Figure I-8. These sediments are generally finer than the surface sediments for the entire profile (compare with Figure I-6).....	26
I-10 Beach changes and buried oil at NOAA's profile N-1 at Point Helen. The plot of four profiles measured during	

LIST OF FIGURES, *cont.*

I-11	Point Helen at low tide on 5 January 1990. Note the presence of gravel swash bars in the intertidal zone that were obviously migrating in a southerly direction.....	29
I-12	Detailed map of Sleepy Bay showing the location of the specific section of Sleepy Bay used as a candidate beach for this analysis	31
I-13	Surface sediment distribution map at the head of Sleepy Bay on 24-26 May 1990.....	32
I-14	Field sketch of NOAA's profile N-18 at Sleepy Bay at low tide on 24 May 1990. Note the presence of multiple berms in the high-tide area. Buried oil occurs on the upper one-third of the profile	33
I-15	Plot of NOAA's beach profile N-18 as it appeared on 1 February 1990. During the fall-winter-spring of 1989-1990, the upper part of the profile was host to multiple migrating berms, the central part was relatively stable, and the lower part contained swash bars from time to time, some of which were associated with the river delta	34
I-16	Plot of estimates of the grain size of the surface sediments at 26 intervals along NOAA's profile N-18 on 24 May 1990. Note that mixtures of pebbles and cobbles predominate.....	36
I-17	Description of sediments in two trenches dug on NOAA's profile N-18 on 24 May 1990. See Figure I-14 for location. Surface armoring is not as well developed in these trenches as it is elsewhere in Prince William Sound.....	37
I-18	Plots of the shoreline profile for September and October 1989, at NOAA station N-1, Point Helen. Oil concentrations are shown in mg/kg	40
I-19	Plots of the shoreline profile for November and December 1989, at NOAA station N-1, Point Helen. Oil concentrations are shown in mg/kg	41
I-20	Plots of the shoreline profile for January and February 1990, at NOAA station N-1, Point Helen. Oil concentrations are shown in mg/kg.....	42

LIST OF FIGURES, *cont.*

I-21	Plots of the shoreline profile for September and October 1989, at NOAA station N-18, Sleepy Bay. Oil concentrations are shown in mg/kg.....	45
I-22	Plots of the shoreline profile for November and December 1989, at NOAA station N-18, Sleepy Bay. Oil concentrations are shown in mg/kg	46
I-23	Plots of the shoreline profile for January and February 1990, at NOAA station N-18, Sleepy Bay. Oil concentrations are shown in mg/kg.....	47
I-24	Comparison of Exxon Valdez cargo oil to mousse collected at Sleepy Bay (May 1990). Note the difference in scale of concentration between the two plots	52
I-25	Comparison of Exxon Valdez cargo oil to oil contained within a tar mat in Sleepy Bay. Note the difference in scale of concentration between the two plots	53
I-26	Comparison of Exxon Valdez cargo oil to a surface sample from Sleepy Bay that is heavily weathered. Note the difference in scale of concentration between the two plots	54
I-27	Comparison of Exxon Valdez cargo oil to subsurface oil buried in the spring tide berm at Sleepy Bay (May 1990). Note the difference in scale of concentration between the two plots	57
I-28	Comparison of Exxon Valdez cargo oil to subsurface oil of the upper intertidal zone at NOAA study station N-18 (May 1990). Note the difference in scale of concentration between the two plots	58
I-29	Comparison of Exxon Valdez cargo oil to subsurface oil of the middle intertidal zone at NOAA study station N-18 (May 1990). Note the difference in scale of concentration between the two plots	59
I-30	Comparison of Exxon Valdez cargo oil to subsurface oil of the lower intertidal zone at NOAA study station N-18 (May 1990). Note the difference in scale of concentration between the two plots	60

LIST OF FIGURES, *cont.*

I-31	Comparison of Exxon Valdez cargo oil to subsurface oil at NOAA study station N-1 upper intertidal zone (May 1990). Note the difference in scale of concentration between the two plots.....	61
I-32	Comparison of Exxon Valdez cargo oil to subsurface oil in the spring tidal berm at Point Helen (May 1990). Note the difference in scale of concentration between the two plots.....	62
I-33	Model predictions of concentrations of total PAHs in pore water in contact with intertidal deposits of subsurface oil on shores of Prince William Sound. (a) The initial concentrations case. (b) Comparison of average case and March case.....	70
I-34	Comparison of concentrations of total PAHs in pore water of sediments collected from oiled shores in Prince William Sound in March 1990, predicted by the model and actually measured in pore water samples.....	77
II-1	TPH concentrations in subsurface sediments at 18 Exxon transects in Prince William Sound from September 1989 to March 1990, for all transects and divided into different energy levels.....	100
II-2	Summary of oil spill self-cleaning processes (modified from Vandermeulen, 1977).....	105
II-3	Sheen sightings reported in 1990 by Exxon crews, through 2 June	124
II-4	Plot of average daily wind speed, tidal range, and number of sheens reported by ADEC during the four-month period beginning 14 November 1989	126
II-5	A: Weekly sheen oil volumes based on Exxon data. B: Weekly sheen oil volumes based on ADEC data.....	128
II-6	Weekly sheens in Prince William Sound, as reported by Exxon.....	130
II-7	PAH profiles for North Slope crude oil and sheen oil sampled in the Bay of Isles in April 1989 (upper) and October 1989 (lower).....	133

LIST OF FIGURES, *cont.*

II-8	Comparison of the analysis profiles of Exxon Valdez cargo oil and a sheen collected at Block Island (May 1990)	134
II-9	Comparison of the ion chromatograms (m/e 85) for the sheen sample collected at Block Island and weathered, non-sheening subsurface oil from Sleepy Bay	135
II-10	Comparison of subsurface sediment from Sleepy Bay (non-sheening oil) to a sample collected at the Barren Islands that readily sheens	137
II-11	Zones of convergence in Prince William Sound	141
II-12	Subtidal profiles off NOAA stations N-1 (upper) and N-18 (lower) in June 1990	151

LIST OF TABLES

	<u>Page</u>
I-1 Lists of sites considered for inclusion as a candidate beach representative of the sheltered pocket beach type for rock washing	18
I-2 Concentration of specific compounds in sediments at the candidate beaches.....	63
I-3 Concentrations of total PAHs in pore water and sediments, and of TPH in subsurface sediments collected from several oiled shorelines in Prince William Sound in March 1990	72
I-4 Concentration of specific compounds in pore water collected at candidate beaches during May 1990	74
II-1 Summary of TPH data for all Prince William Sound sediment samples from Exxon's winter monitoring program.....	95
II-2 Summary of TPH data for selected transect Prince William Sound subsurface sediment samples from Exxon's winter monitoring program.....	97
II-3 Regression analysis for TPH data from principal transects	99
II-4 Summary of biological recovery rates for various types of disturbance.....	118
II-5 Subtidal observations at site N-1, Point Helen.....	152
II-6 Subtidal observations at site N-18, Sleepy Bay	154
II-7 Concentration of specific compounds in subtidal sediments at the candidate beaches	155
II-8 Summary of biological recovery rates for previous oil spills	171

I. DEFINITION OF STUDY

I.A. OBJECTIVE

I. A.1 STATEMENT OF THE PROBLEM

Cleanup of the EXXON VALDEZ oil spill has required the use of various shoreline treatment techniques, many of which are new to oil spills. Water flooding, omnibooms, and application of fertilizers were innovative approaches developed and modified for use in addressing the cleanup problems in 1989. One of the shoreline treatment problems in 1990 is the presence of oil which has penetrated into porous sediments and persisted through the first year of fall/winter/spring storms. It is believed that the approved shoreline treatment techniques for 1990, namely, manual removal, spot washing, and bioremediation, will not effectively remove subsurface oil this year. Bioremediation has been shown in laboratory and recent field studies to induce higher respiration rates to depths of 15-30cm, yet the rates are lower than at the surface. The ongoing monitoring program of the use of Inipol and Customblen fertilizers will help answer the questions about the degree and depths of enhanced degradation resulting from nutrient augmentation.

In the event that none of the approved techniques adequately address the subsurface oil treatment problem, the Federal On-Scene Coordinator requested that Exxon determine the feasibility of use of an excavation/rock washing process. Exxon agreed to manage the design and demonstration of a rock washer for removal of subsurface oil as long as an assessment of the net environmental benefit was conducted simultaneously with the engineering development. A committee was formed with representatives from the National Oceanic and Atmospheric Administration (NOAA), State of Alaska, and Exxon, with NOAA designated as the chair, to conduct a Net Environmental Benefit Analysis (NEBA), working in close conjunction with the Engineering Process committee. The NEBA committee was charged with the task to determine if there were net environmental benefits from the excavation and washing of oiled sediments, and return of treated sediments to the excavated site over natural cleansing and the use of approved 1990 treatments.

I. A.2 GENERAL APPROACH

To determine the net environmental benefit of excavation and rock washing of oiled sediments, the NEBA committee developed preliminary selection criteria to identify the types of beaches that would be candidates for rock washing. Based on the assumptions that 1) approved or developing techniques would be adequate for treatment of surface oil, and 2) natural cleansing or bioremediation may be effective for removal of subsurface oil to depths of 10-15cm, this report focuses on deep subsurface oil. The following general criteria were used to identify candidate beaches:

- 1) The degree of subsurface oil contamination was classified as OP*, OL*, or OR* during the Spring Shoreline Assessment Team (SSAT) survey.
- 2) The depth of oil is >15cm.
- 3) The thickness of the oiled sediment zone is >15cm.
- 4) The substrate type is mostly sediment of cobble or finer grain size.
- 5) TAG recommendation was bioremediation or mechanical relocation/till.
- 6) The shoreline was a chronic source of sheens.

*OP = Oil fills pore spaces between sediment particles

OL = Lens or layer of buried oiled sediments

OR = Residual oil on sediments or in pore spaces but not saturated

The committee felt that it was important to identify specific beaches so that the actual operational constraints and environmental conditions of the sites would provide the basis for evaluation. Because so many parts of the evaluation had to be based on the literature and extrapolation of data, it was important that real sites be included. Three specific candidate beaches were to be identified as representative of the range of shoreline types being considered for rock washing treatment. These shoreline types were initially identified as:

- ☐ Exposed, outer beach with long stretches of relatively uniform sediments and little to no operational access problems.
- ☐ Moderate-energy shoreline with highly variable substrate.

- ☐ Sheltered, pocket beach with relatively small areas needing treatment and limited space for onshore operations.

It was agreed that one of the candidate sites should also include an anadromous stream mouth.

Using site-specific examples, the remainder of Section I describes the engineering process envisioned for excavation and rock washing and the existing physical, chemical, and biological conditions of the candidate sites. In the first part of Section II, the persistence and impact of the subsurface oil under a no-treatment condition is assessed. In the second part of Section II, the impacts associated with excavation and rock washing are assessed. Section III consists of a summary statement on the impacts and tradeoff considerations for excavation and rock washing as a shoreline treatment technique.

LB. DESCRIPTION OF EXCAVATION ROCK WASHING

I.B.1 GENERAL TECHNOLOGY

The excavating rock washer is a mechanical process for removing oil from excavated beach rocks and sediments using heated sea water. All equipment components and specifications have not yet been determined, but most characteristics of the process can be identified. Conceptually, this process is intended to be a self-contained, permitted technology that would be capable of excavating and cleaning coarse and most finer beach sediments and replacing the clean material back on the beach. Process objectives include minimization and containment of process wastes and control of suspended sediment plume formation resulting from the excavation.

The equipment used in this process is based on that used extensively in placer mining throughout Alaska, and in gravel classification and washing in Alaska and throughout the United States. The method involves excavating the contaminated material, sorting it according to size, and running it through the washing or tumbling equipment, then replacing the treated and clean sediment near its original location. Generally, the finest sediments become waste and would not be returned to the beach.

To satisfy the need for self-containment and the minimization of wastes, this equipment is augmented with additional equipment capable of excavating oiled beach sediments, separating oil from the process water, cleaning the process water of entrained sediment, recycling the process water, and dewatering and replacing the excavated and cleaned sediment back on the beach. Since the entire process requires an assorted number of individual pieces of varying bulk, and since large volumes of oily wastes are anticipated, ancillary equipment is required. This ancillary equipment would be used to deploy materials onto and off the beach, berth and feed support personnel and store generated waste water, oily slop and contaminated sediment.

I.B.2. PROCESS FLOW DIAGRAM (PRELIMINARY)

See Figure I-1.

I.B.3. OVERVIEW OF PROCESS CAPABILITIES

This equipment does not yet exist. Although smaller-scale equipment developed primarily to clean sand or pebble beaches exists, nothing of the scale and complexity proposed for the present application has ever been built. The selected process is composed of field-tested components. However, operation as a combined unit in an adverse environment (on a barge and between barge and beach) make the following capabilities somewhat uncertain in the field.

- a. The unit can operate at a process rate of 100 cubic yards per hour.
- b. The unit is capable of handling sediment sizes from silt to 24" in diameter although it is not designed for excessive fine sediment or friable sediment loads.
- c. The unit is capable of operating both onshore as well as from a mobile offshore platform, and can be deployed on any size beach where physical access is possible.
- d. The process uses salt water maintained at 160°F or greater to clean the sediment.

- e. The process design minimizes the recycle water rate and make-up water rate. Discharge of any process water as an effluent stream will not be considered as an acceptable option unless it satisfies all laws and regulations concerning discharge standards.
- f. The process dewateres all processed sediment in order to minimize the water content of the processed sediment to an acceptable level for recontouring on the beach.
- g. The unit is designed to minimize rock crushing or breakage. However, when sediments containing both sandstone and shale are processed, shales may be pulverized and could generate heavy sediment loadings when returned to a beach.
- h. The oil content of the final cleaned rocks will be less than 800 parts per million (ppm) total petroleum hydrocarbon (TPH) on composite samples from a representative distribution of sediment sizes.
- i. The process is designed to accomplish the job using only salt water and not any other chemicals to enhance the cleaning of rocks. However, the process has the flexibility to allow addition of chemicals to enhance treatment of recycled process water.
- j. The process will release oil and fine particles during excavation that can be carried by waves and water around and away from the excavation site. These releases must be controlled by other means, such as booms and/or sediment curtains.

I.B.4. OPERATIONAL CONCEPTS AND LOGISTIC CONSIDERATIONS

The excavating rock washing operation entails a sequence of activities and events that must be considered in any evaluation of environmental impact:

Site Selection and Pre-Operational Preparations

The selection of a beach site for excavation rock washing would entail a beach characterization based on existing data, field observation, and measurement. This characterization will yield operational parameters, such as work area, slope and stability of beach, needs for site preparation,

volume and distribution of sediments to be excavated, working conditions, and access to areas to be excavated. The characterization will help determine how the equipment will be mobilized and deployed. In particular, it will help determine which equipment configurations will be employed (and which operations will be conducted) on-beach versus which off-beach. The process is capable of both modes of operation, although off-beach would be generally preferred due to greater mobility and flexibility and lower intrusiveness.

Mobilization

All necessary equipment, barges and boats involved with the excavation project would be marshalled at a nearby port, Valdez, Seward or Whittier, with industrial capabilities. Portable equipment would be loaded onto the appropriate transportation and the process components would be assembled and checked. All elements would be tested to ensure each one is operational and last-minute modifications made. Pollution prevention controls on the barges would be ascertained. A review of all safety, operational, logistical, weather, and pollution plans would be accomplished and last minute changes incorporated.

Site Preparation

Double oil containment booms would be put in place around the area to be excavated and the waste storage and process transporting barges to contain any released oil or sheening from the work site. A crew with boats and cleanup equipment would be on standby for any spill cleanup. Engineering controls would be in place to reduce silt loadings from the excavation. Prior to any process excavation, large debris, such as logs, or any other non-processable material would be gathered and stockpiled on the beach for later replacement or disposal. Clean sediments extending to a depth of approximately 30cm, as much as practical, could be set aside on the beach for later replacement.

Sediment Washing, Dewatering, and Quality Control

Oiled sediments, as well as sediments outside the oiled area (due to a need for a working area and excavation layback), would be excavated.

Rocks larger than the equipment capacity would be separated and stockpiled on the beach for later replacement. Rocks too large to move with the equipment being utilized will remain in place.

The excavated sediments would be size classified then dumped into primary washing units and washed with sea water heated to 160°F or greater. The water would then be recycled to reduce heating requirements and minimize wastewater volumes. The processed sediment would then be dewatered and, if the TPH content is at or less than 800 ppm as determined by an agreed upon test protocol, the processed sediments would be returned to the beach. Dewatering produces the low water content necessary to maximize the stability of returned sediments. Excess water and the oil removed, plus a portion of the fine glacial silts that cannot be processed to the 800 ppm TPH level (probably sediments less than 1mm in size), would be separated for eventual disposal.

The most probable mode of operation would have earth moving equipment and conveyor stations on the beach and all other process equipment on a barge off the beach. Another choice would be operation of the entire process on the beach and do away with the necessity of an offshore processing unit. This scenario is unlikely due to the actual size of the components of the process equipment needed for mobility to "follow" excavation equipment as it progresses along the beach and the real possibility of severe weather damage to the processing equipment.

At a minimum, the equipment on the beach would be a couple of backhoes and/or front end loaders and the termination of the belt conveyor systems. The remainder of the rock wash process equipment would be based on a barge. This would eliminate any construction pads (leveled areas to place the process on) on the beach and would reduce the impact to non-oiled beach segments.

Oil/Water/Solids Separation and Quality Control

The separated oil, sludges, contaminated sediments and oily water would be transferred to a tank on a U.S. Coast Guard-certificated petroleum/waste oil tank barge. When full, the barge would be taken to a

nearby shore facility to further process the waste. No secondary concentrating of oily waste is anticipated to be done on-site.

Handling, Transfer, Storage, and Disposal of Waste

All wastes generated would be transported to a land-based facility for treatment, recovery, or further dewatering and concentration. It is anticipated that the oily solid wastes generated by this process would be transported to an approved landfill.

Control of Oil Leaching, Sheens, and Glacial Fines

A double boom will be in place around the beach and the process and waste storage barges to contain sheens and sediment released as a result of the beach excavation. Pads and pompoms can be used to "wipe up" sheens or concentrations of oil.

Backfill and Beach Recontouring

To the extent that the working area allows, and the rate of return of washed material, portions of the excavation could be backfilled during the processing operation. Prior to demobilization at the particular site, the beach would be re-contoured to original conditions as much as possible.

Frequency of Movements of Equipment

Work on the beach will be governed by the weather conditions encountered and the tide cycle. Assuming that the weather is not a factor, it is anticipated that the work day could be anywhere from eight to fourteen hours. Movements by vessels along the beach would be a function of the excavation progress being made. It is anticipated that the repositioning of equipment would be made at high tide and generally once or twice in a 24-hour period. Depending on the availability of suitable waste storage barges and their capacities, movement to the shore processing facility would be made to coincide with demobilization or when the barge is loaded to its design capacity. A possibility exists, due to barge capacities and the amount of waste that might be generated, that in order to continue uninterrupted excavation operations, more than one waste oil barge would be necessary.

Demobilization

On complete excavation and cleaning of a segment and final beach re-contouring, with agreement by concerned parties, the equipment will be moved to the next beach segment targeted for cleaning and the process will begin again. On termination of all cleaning operations, all vessels will either be released from the site or returned to the port of embarkation for final debrief, unloading and cleaning of the process components.

I.B.5. EXPECTED PROCESS AND ANCILLARY EQUIPMENT

<u>Equipment: Purpose</u>	<u>Type/Example/Size</u>
Debris Removal	Frontend loader tracked w/5 yd ³ /bucket
Conveyor(s)	Covered, w/hand cap. up to 24" rock, 100'-120' length
Water Heater/Boiler(s)	@ 65 mbtu, Area: 15' x 40'
Rock Washer	30' x 7' trommel w/supports and 3- stage vibrating screen on 10'x 20' base
Oil/Water/Solids	2 to 4 sand screws 25' length, settling tanks, separation & dewater pumps, sieves, hydroclones, hoses, pipes; Area 140'x 20'
Beach Regrading	Bulldozer, w/gen. purpose blade
Excavation and Washer Feed Loading	Backhoe(s) and front end loader(s) w/4 or 5 cubic yds bucket
Waste Tank Barge(s)	30k-100k bbl capacity approx 50'x 200' dimension
Crane	10-60 ton capacity
Landing Craft(s)	Handle beach excavation equipment, approx. 3 @ 70'x 30'

Equipment: Purpose. cont.

Type/Example/Size

Deck Barge/Liftboat

50'x 200'; house process equipment

Oil Containment Boom-36"

5,000'-10,000'; around process barge and beach excavation area

Generators

Power auxiliary equipment/lights

Support Vessels and Aircraft

Tugboats (Ocean)

(2) @ 1800-5000 hp;
standby/handle/move barge(s)

OSV/Crewboat

150-180'; equipment and
berthing/messing and A/C landing
pad

Workboats

15-25 ft, transportation to and from
beach, boom deployment

Helicopter

Medical evacuation and rapid
transportation

Personnel

20+ pers to run process/excavation;
50+ pers Support/VsIs/Contract/Sup/
Regulatory

Positions. Locations of Process and Ancillary Equipment

Debris Removal

Beach

Excavation

Beach

Conveyor(s)

Beach excavation area to barge and
back

Water Heater/Boiler(s)

Deck barge/liftboat

Rock Washer

Deck barge/liftboat

Oil/Water/Solids

Deck barge/Liftboat (separation & de-
water)

Beach Regrading

Beach

Waste Tank Barge

Seaward of Deck barge/Liftboat

Positions, Locations of Process and Ancillary Equipment, cont.

Crane	Deck barge/OSV
Landing Craft(s)	Alongside OSV/Deck barge
Oil Containment Boom-36"	OSV/Deck barge/Deployed around the work area
Tugboats (Ocean)	Seaward of deck barge
OSV/Crewboat	Seaward of deck barge
Workboats	OSV/Deck barge/Beach
Helicopter	OSV
Personnel	3-7 pers beach; remainder on vsls/barge
Generators	Process barge/beach

I.B.6. OPERATIONS

Equipment Position

It is anticipated that the deck barge (draft approximately six to eight feet) handling the process equipment will be anchored an expected 50-100 feet from the beach to safely support the anticipated draft in the expected sea, wind and current conditions. Other vessels will be anchored or stationed in the immediate vicinity to best support the process. If a lift boat or jack-up barge is utilized, the distance to the beach will be less than 50 feet, with the distance used depending on bottom conditions such as sediment type and slope. See Figure I-2 for a schematic representation.

Beach Progress

Assuming a 12-hour work day with no breakdown and weather considerations and an excavation cross-section of 25 yards and 0.66 yard depth (60 cm) at a rate of 100 cubic yards per hour, progress up the beach would be at a rate of about 6 yards per hour or about 250 feet per day. Equipment would probably be moved every 12- to 24-hour workday. In actuality, allowing for equipment breakdown, maintenance, and weather-affected delays, progress would likely not exceed 100-150 feet per day.

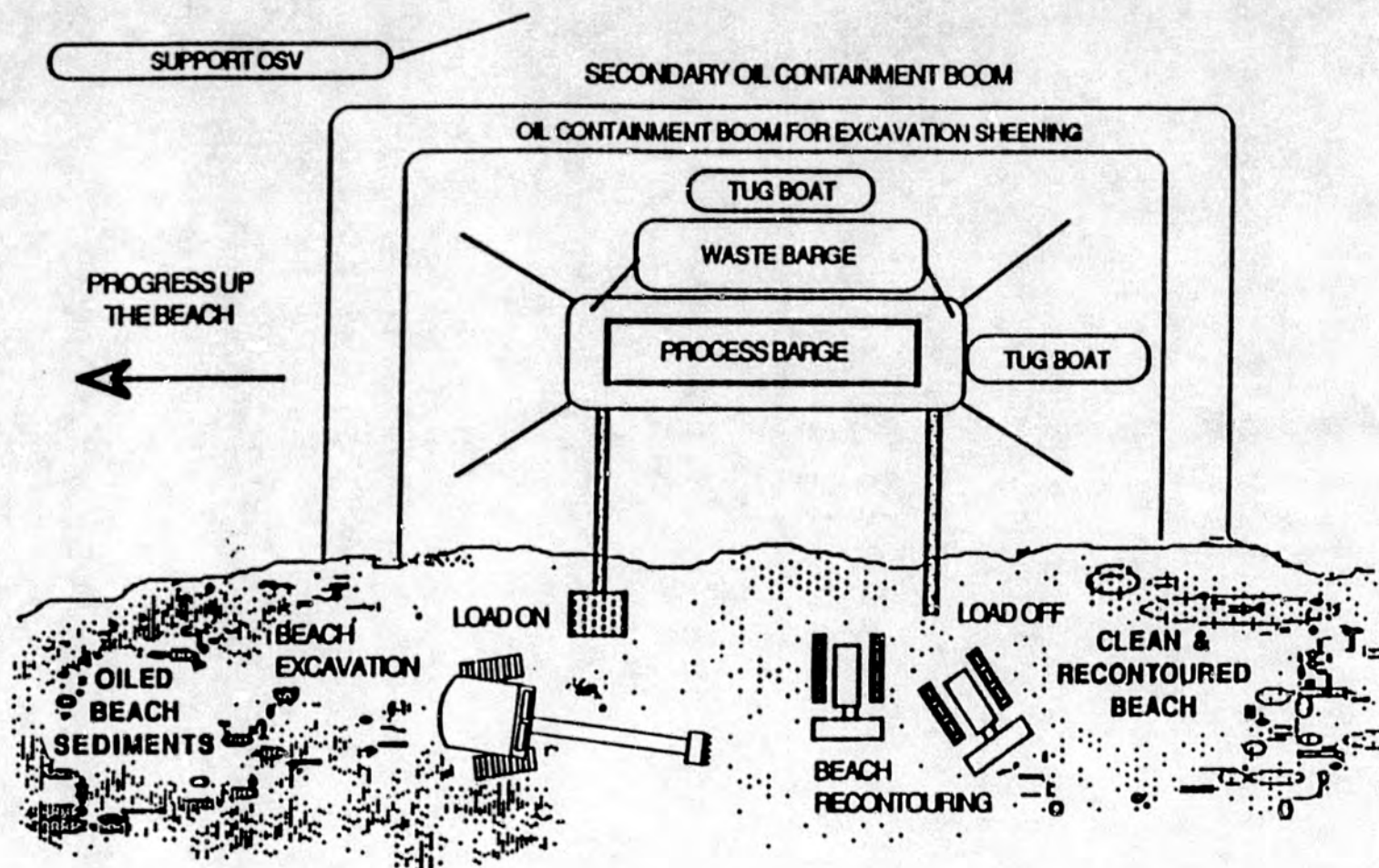


Figure I-2. Beach excavation rock washing project.

Weather Considerations

If the equipment is barge mounted it is anticipated that the weather window would be limited to seas four feet or less and winds less than 20 knots. Barge stability is important for process water clarification purposes and any gravimetric laboratory sampling analysis. A comprehensive heavy weather plan would have to be devised and implemented with contingent "safe anchorages" identified to which the process equipment, waste storage barges, and auxiliary vessels could be moved.

Oil Spill Contingency

Any sheens generated by the excavation process or resulting from handling of oily sediments over water and conveying could be handled with pads and pompoms. However, the concentration of oil in the process water could result in a more significant release through equipment failure.

USCG Marine Safety Office Valdez, Alaska Oil Spill Contingency Plan should be reviewed and implemented as applicable.

State of Alaska Oil Spill Contingency Plan should be reviewed and implemented as applicable.

A comprehensive survey review of the tidal current conditions and bottom composition, contour, and sediment conditions would have to be made to provide for the safe anchoring and navigation of process equipment and all auxiliary vessels.

Secondary Impact: Waste Generation, Air Emissions, Fuel Consumption, and Noise Generation

Machinery involved with the process would produce noise at a level of over 110 decibels (dB). This is a high level of noise that would persist in an operating area during daily work periods of between 8 to 14 hours. At about 1/2 mile away, the perceived noise level would be over 62 dB, well above levels regarded as potentially disturbing to eagles based on 1/4 restrictions for skiffs that produce 90 dB.

It is anticipated that oil/water/sediment wastes will be generated at a rate of up to one barrel per cubic yard of sediment processed. These wastes

will include removed oil, oil sludges, oil/sediment complexes, suspended sediments and water. About one-half gallon per barrel of this waste will constitute removed oil.

These wastes would likely be transported to Valdez, Seward or Whittier ports for treatment (liquids) or for further processing and concentrating for ultimate disposal at a landfill (solids).

Each of these wastes have a potential to impact the environment as a result of spills or accidents causing contamination of beaches, surface waters, soil, and ground water with oil or fine sediment. See Section II.B.6 for a further discussion of potential waste impacts.

Fuel use and air emissions are also significant. For example, if all oiled subsurface sediments at Sleepy Bay were processed, a total of about 400,000 gallons of fuel would be used to run equipment, support vessels, and aircraft, and 300,000 pounds of regulated air pollutants would be emitted over the 4-6 week period required for processing. Waste generation, air emissions, and fuel consumption for Sleepy Bay (LA-16 through LA-20) are illustrated schematically below:

SEDIMENTS EXCAVATED	17,000 cubic yards
Fuel use	400,000 gallons

WASTES GENERATED

Air pollutants	300,000 pounds
Wet skimmed oil	12,000 gallons
Wet, oily solid waste	500,000 gallons
Oily wastewater	168,000 gallons
Processed beach sediment	17,000 cubic yards

LC. DESCRIPTION OF CANDIDATE BEACHES

I.C.1 SELECTION CRITERIA

Using the general criteria outlined above, members of the NEBA Committee developed a list of candidate beaches. The list was compiled using:

- 1) the SSAT database and search criteria on oil type, thickness, and depth;
- 2) the Alaska Department of Environmental Conservation (ADEC) beach profile database; and
- 3) personal observations of the committee members.

It was agreed that Point Helen and Sleepy Bay were the best candidates for the exposed outer beaches and moderate-energy shoreline with variable substrate, respectively (Figure I-3). Specific parts of each area were identified as study areas. However, the initial segment selected for the candidate for the sheltered, pocket beach, KN500, was subsequently rejected because of the presence of an active eagle nest at the site, which restricted all approaches. It was very important that the committee members be able to survey each site with rock washing issues in mind, so another candidate for the sheltered beach type was sought. Several recommended sites were evaluated and none was found to be adequate. After two weeks of effort to identify and field-check sites, it was decided to proceed with only two sites. During the two-week period, 22 sites were suggested, with none of them selected as an appropriate candidate site for the purposes of this study. Table I-1 lists the sites considered for the sheltered pocket beach candidate site (by segment number), the team who inspected or researched the site, and the reason for rejection. It should be noted that rejection of a site as a candidate beach for this study does not necessarily mean that it is not an appropriate site for rock washing.

In the following sections, each of the two candidate beaches is described in detail.

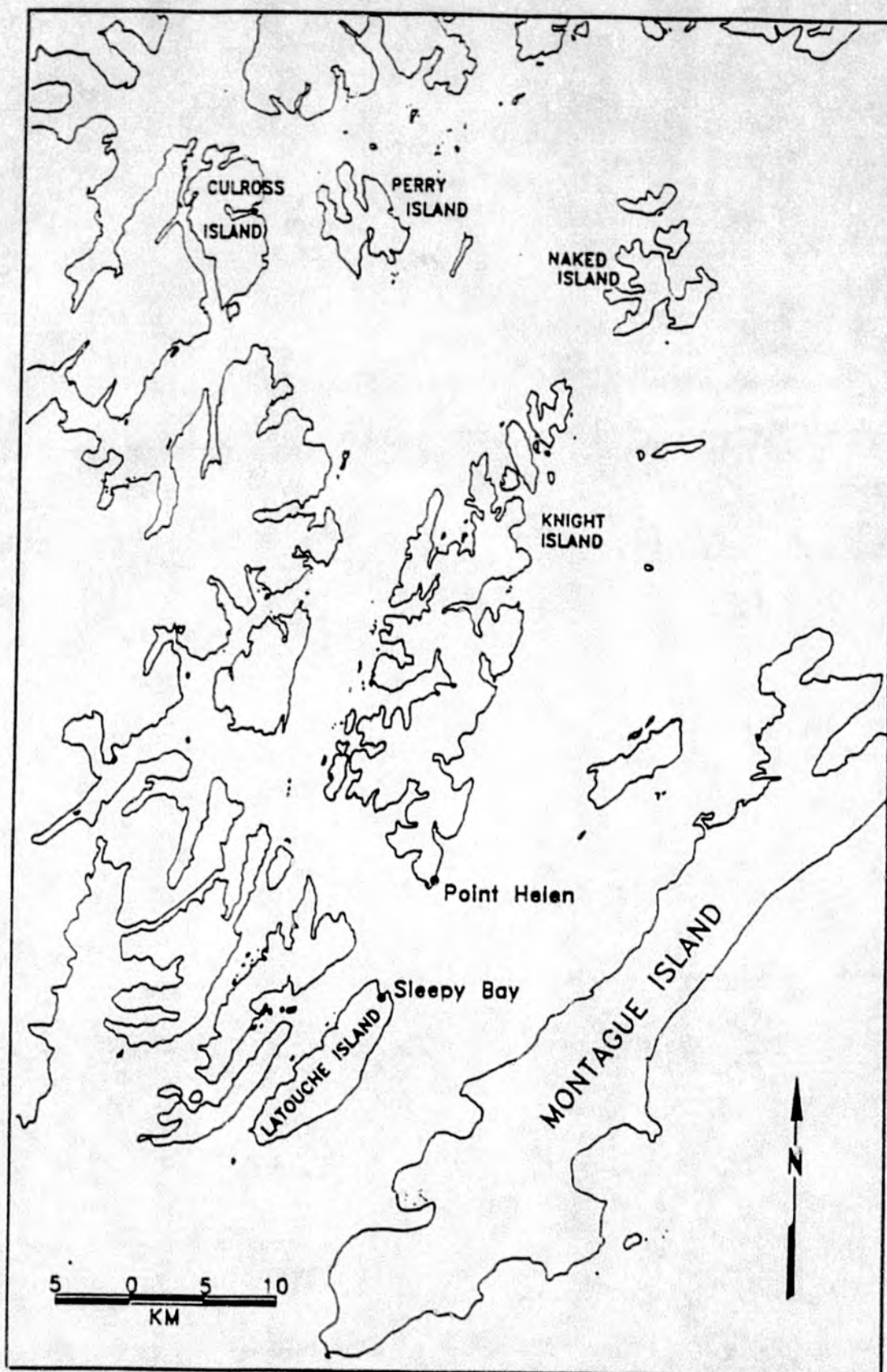


Figure I-3. Location map showing the two candidate beaches at Sleepy Bay and Point Helen.

Table I-1
 Sites Considered for Inclusion as a Candidate Beach
 Representative of the Sheltered Pocket Beach Type for Rock Washing

<u>Site</u>	<u>Rejected By</u>	<u>Reason for Rejection</u>
AE-05	NOAA	Substrate
BP-16 (Marsh Lagoon)	Exxon	Lack of access
CR-05	NOAA	Shallow peat substrate
DI-62	ADNR	Lack of access
DI-67	ADNR	Insufficient oil
EB-11	Consensus	Insufficient oil
EL-10	NOAA	Unapplicable substrate
ER-20	Exxon	Eagle restriction
EL-56	NOAA	Insufficient oil
IN-20	Consensus	Insufficient oil
IN-22	Consensus	Applicable area very small; peat layer limits penetration
KN-113	Consensus	Insufficient oil
KN-121	Consensus	Lack of access
KN-132	NOAA	Unapplicable substrate
KN-134	NOAA	Oil not deep enough
KN-135	Consensus	Lack of oil penetration
KN-211	Consensus	Insufficient oil
KN-213	Exxon	High energy site
KN-500	Consensus	Eagle restriction
LA-17	Consensus	Not low energy
PR-16	Consensus	High/moderate energy Eagle restriction
SP-19	Consensus	Very small beach; limited depth, good bioremediation site

I.C.2. GEOMORPHOLOGY

Point Helen

Introduction. This beach is located on one of the more exposed sites in Prince William Sound. Consequently, it contains abundant coarse material—pebbles, cobbles and boulders—that shows signs of frequent transport by wave-generated currents (i.e., rounding and sorting). Due to uplift in the area on the order of 8 feet during the 1964 earthquake, the beach has not completely readjusted to an equilibrium profile. The specific part of Point Helen used as the candidate beach was 100m to the south and 200m to the north of NOAA Station N-1. Exxon's stations AP-9 and AP-10 are north and south, respectively, of the candidate beach section.

The Beach Profile. The field sketch in Figure I-4 and the profile in Figure I-5 show the morphology of the beach at Point Helen at NOAA's station N-1 on 24 May 1990, which is typical of the entire beach area under consideration in this report. There are three morphologically distinct components of the profile:

1) High-Tide Berms

The upper ± 10 m of the profile was host to a series of migrating spring-tide and storm berms between September 1989 and May 1990, as shown by data collected during NOAA's winter monitoring program (Advanced Technology, Inc. and Continental Shelf Associates, Inc., 1990). The finest surficial materials occurring on the beach (down to pebble size) are found in this area.

2) Stable Central Ramp

A cobble to boulder armor has formed over the surface of this central (10-25m) portion of the profile, which has shown almost no change over the past 9 months. The ratio of boulders to cobbles increases in a seaward direction.

3) Low-Tide Bar Zone

This zone, which extends from 25m to the low spring tide line (± 60 m), periodically contains asymmetric bars built by wave action called swash bars. These bars, which characteristically migrate toward the south, may attain heights up to 40 cm, as shown by the survey on

PROFILE ANGLE 106 (true) WAVE HT. 2.4M

SEDIMENT TYPE B/C/P

COBBLE/COBBLER PLATFORM

HEAVY OILED DEBRIS

SHALLOW IMPINGING

BURIED COB

C/S

WAVE

MOSTLY COBBLES

ALGAE

MUD

10/1/72

20

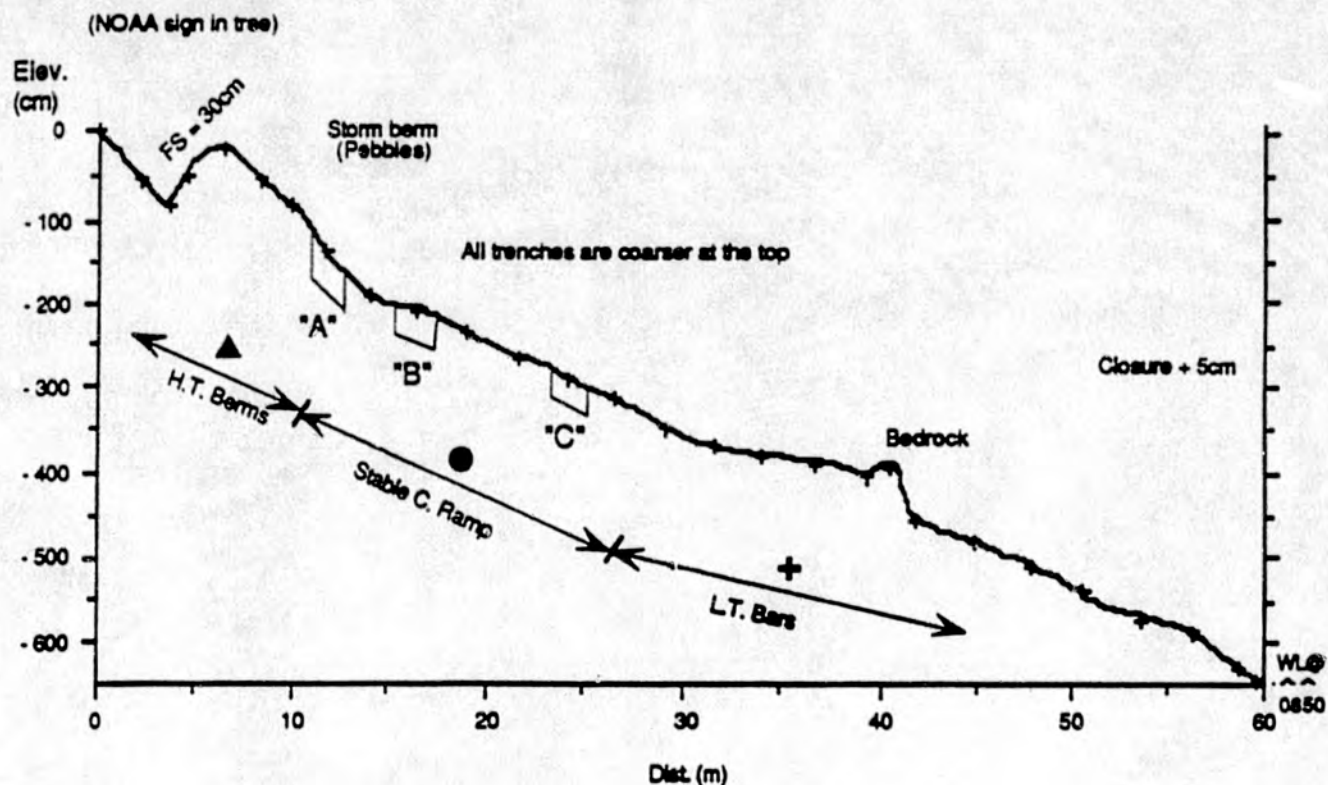


Figure 1-5. Beach profile at NOAA's station N-1 at Point Helen that was measured at low tide on 24 May, 1990. The beach is classified morphologically into three zones: (1) high-tide berms, an area subject to fluctuations of berm levels during storms and spring tides; (2) stable central ramp, bypass zone with an armor of cobbles and boulders; and (3) low-tide bars, boulder/cobble zone that sometimes contains gravel swash bars.

1 February 1990. The surface material is mostly boulders, but patches of bedrock also occur within this zone (Figs. I-4 and I-5).

Composition and Grain Size of Beach Clasts. - The pebbles, cobbles and boulders of Point Helen are no doubt derived locally, probably from outcrops exposed along the shoreline to the north. They are quite hard and do not crumble readily. The composition of the clasts is variable, with the following possibilities (in decreasing order of abundance):

- 1) Slightly metamorphosed deep-water sandstones.
- 2) Dark gray-black or reddish-brown hard siltstone and argillite.
- 3) Miscellaneous basaltic lava, metamorphosed conglomerate, and others.

NOAA's field team measured the detailed distribution of grain size along profile N-1, which is representative of the entire Point Helen area, on 24 May 1990. Careful estimates were made of relative abundance of clast type - pebbles (P), cobbles (C), boulders (B), and granule/sand (G/S) - at 25 evenly-spaced intervals along the profile. These results were plotted on the ternary diagram shown in Figure I-6. The distribution of clast sizes on the surface of the profile is shown on the map in Figure I-7. These diagrams indicate that the surface clasts of the high-tide berms are mixtures of cobbles and pebbles, the stable central ramp has a surface armor of cobbles and boulders, with cobbles predominating, and the low-tide bar zone is dominated by boulders, with cobbles typically making up 25-30% of the total.

Over the winter monitoring period, fourteen trenches were dug and described on this profile. Three were dug on 24 May 1990, and their descriptions are given in Figure I-8. These descriptions show that, in every case, an armor of coarse material overlies fine material at depth. The plot of the estimated grain sizes of the trench sediments on the ternary diagram in Figure I-9 emphasizes further the finer-grained nature of the deeper sediments (compare with Figure I-6).

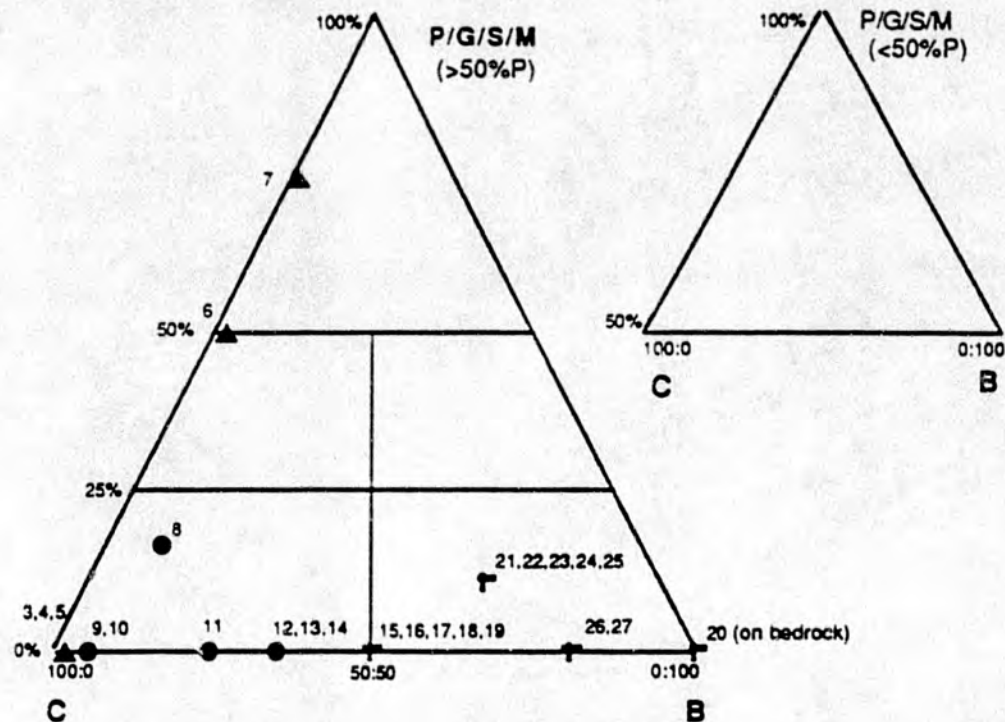
With regard to the rock-washing scenario, only the sediments in the zone between 12 and 21 m would be of interest, because that is where the buried oil occurs (see Figure I-10). The surface layer of sediments in that zone average: 6% B; 74% C; and 20% P. However, the subsurface

ZONAL GRAIN SIZE DESCRIPTION

PROFILE: N-1
DATE: 24 MAY '90

LOCATION: POINT HELEN

X PROFILE STATIONS -OR-
— TRENCH DESCRIPTIONS



	PROCESS ZONES	PROFILE INTERVALS
▲	High-Tide Berms	3 - 8
●	Stable Central Ramp	9 - 15
✚	Low-Tide Bars	16 - 27

NOTES FOR VERBAL DESCRIPTION:

- ▲: Cobble storm berm with welded pebble spring berm.
- : Cobble ramp, becomes increasingly boulder-bearing seaward.
- ✚: Boulder platform, cobbly and pebbly, no relief in May but showing swash bar development earlier (e.g., Dec. '89 to Feb. '90).

Figure I-6. Plot of 25 estimates of grain size of surface sediments along NOAA's profile N-1 on 24 May 1990, with respect to relative amounts of boulders (B), cobbles (C), pebbles (P), granule (Gr), sand (S), and mud (M). The beach zones within which the estimates were made are indicated by symbols (▲, ●, ✚) and the numbers by the symbol represents the profile intervals at which the estimate was made. Profile intervals were usually 1.5-2.0 m apart. Note the clear segregation of size by beach zone, with a distinct increase in grain size in a seaward direction.

N - 1 Point Helen
Surface Grain-size Distribution
24 May 1990

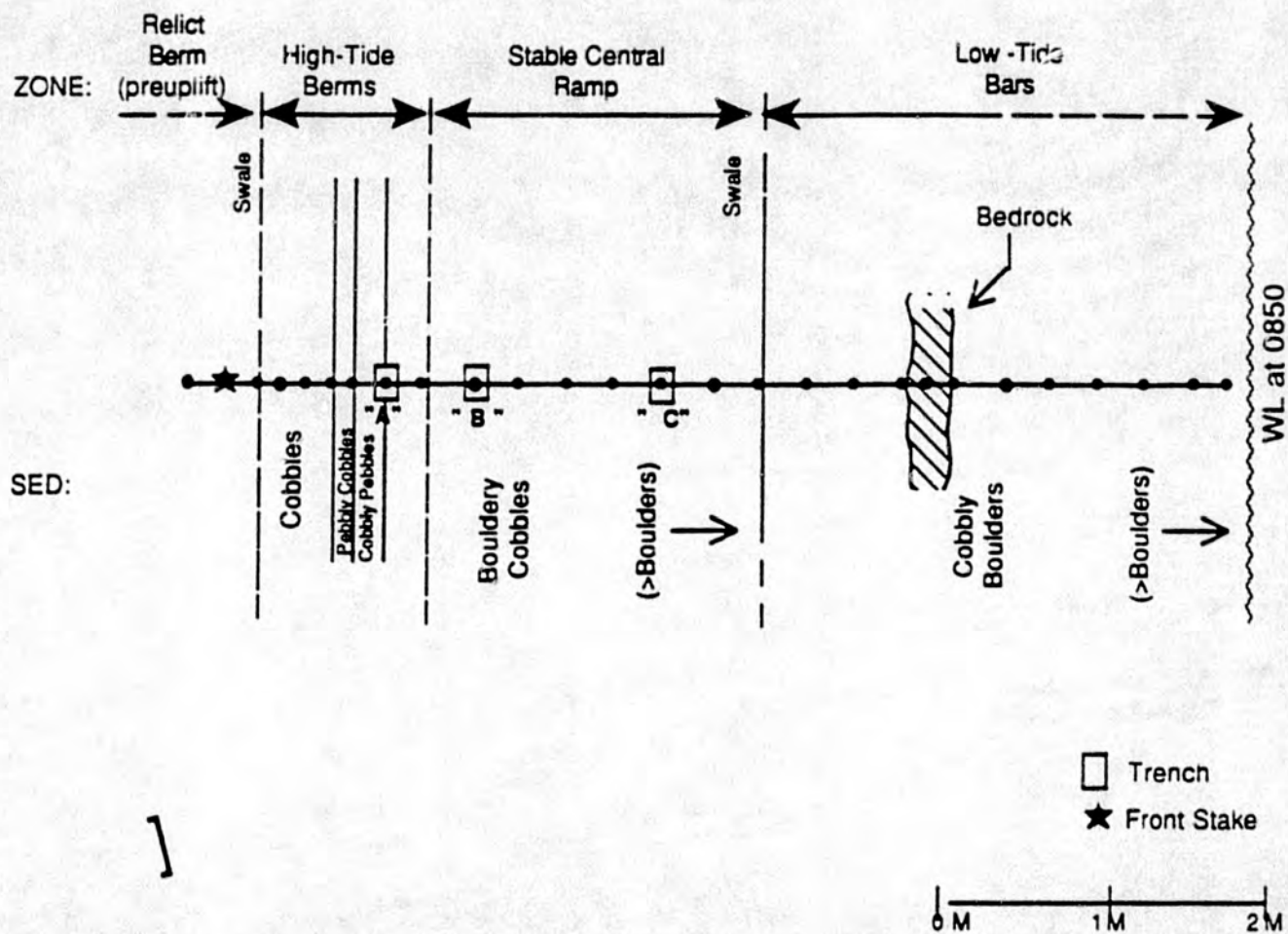
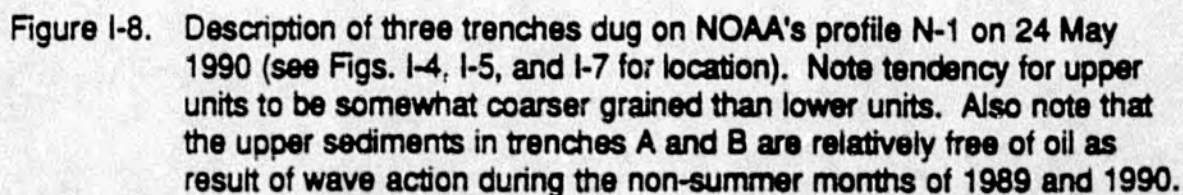


Figure I-7. Distribution of grain size of surface sediments adjacent to NOAA's profile N-1 on 24 May 1990. Dots along profile line indicate points where grain size estimates were made.

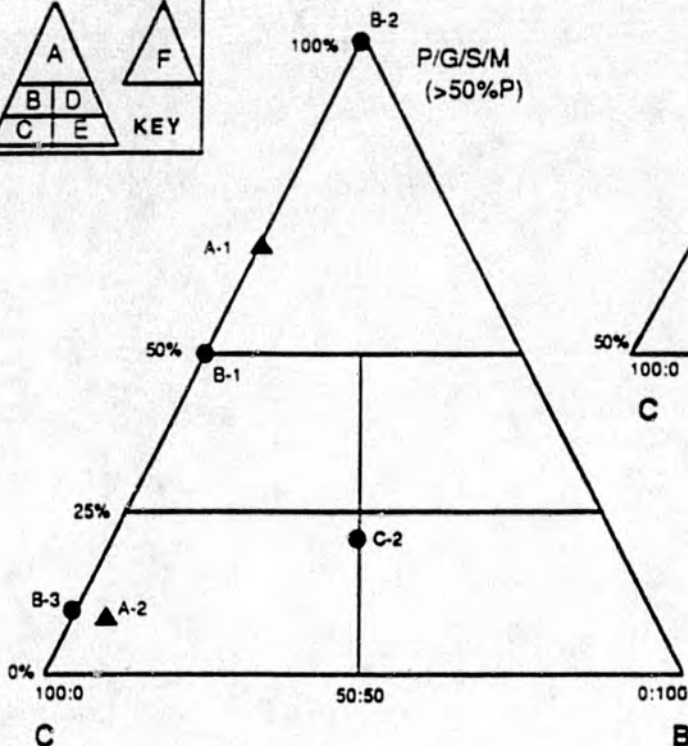
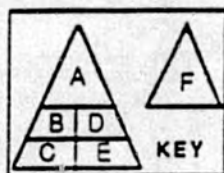


ZONAL GRAIN SIZE DESCRIPTON

PROFILE: N-1
DATE: 24 MAY '90

LOCATION: PT. HELEN

— PROFILE STATIONS -OR-
X TRENCH DESCRIPTIONS



	PROCESS ZONES	TRENCH
▲	High-Tide Berms	"A"
●	Stable Central Ramp	"B" & "C"
⊕	Low-Tide Bars	

NOTES FOR VERBAL DESCRIPTION:

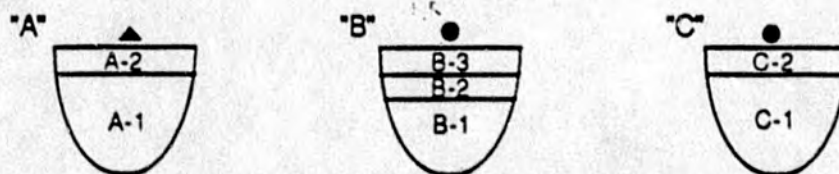


Figure I-9. Plot of grain size estimates for sediments from the trenches described in Figure I-8. These sediments are generally finer than the surface sediments for the entire profile (compare with Fig. I-6).

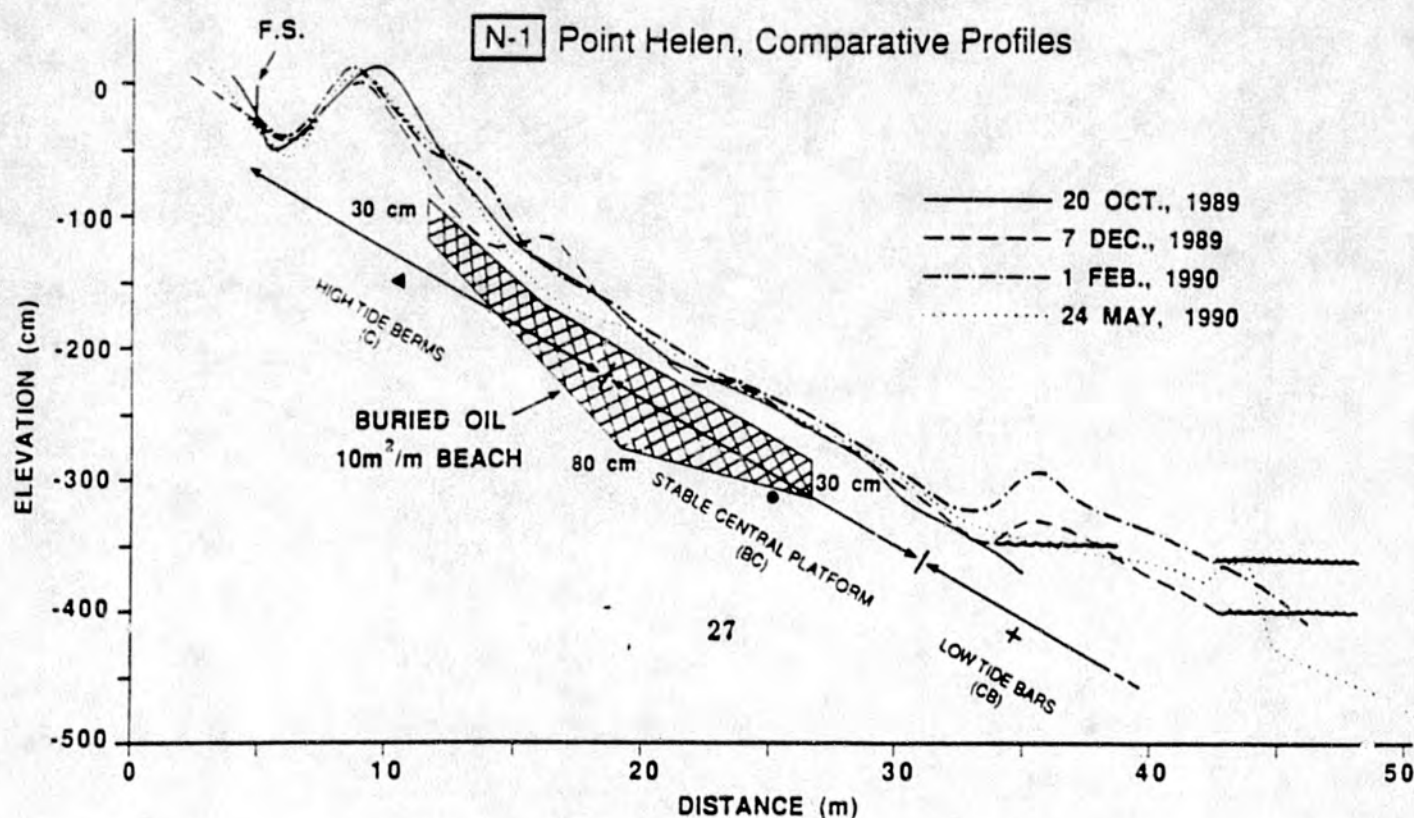


Figure I-10. Beach changes and buried oil at NOAA's profile N-1 at Point Helen. The plot of four profiles measured during the fall-winter-spring interval of 1989-90 reflects the morphological signature of the three designated beach zones: (1) migrating berms in the upper zone; (2) relative stability in the central zone; and (3) migrating bars in the lower zone.

sediments described in the trenches are considerably finer: 1% B; 58% C; and 41% P. If one assumes that in the rock washing process five times more material would be derived from the subsurface than from the surface, the sediments to be washed at Point Helen would have the following grain size:

<u>Sediment Type</u>	<u>Percent</u>	<u>Average Size</u>
Boulders	2	40 cm
Cobbles	61	13 cm
Pebbles	30	2 cm
Granule/Sand*	7	3 mm

Energy Level and Beach Dynamics. - This beach is exposed to the east, the direction from which the dominant winds blew during storms in the fall-winter-spring period of 1989-90, according to data gathered at NOAA's meteorological stations at Lone Tree and Danger islands. The effective fetch distance ranges from 15-20 km in a due easterly direction up to 45-50 km to the NNE. No seasonal measurements of wave or current conditions are available for the site.

As implied above, there is a significant amount of clast transport on this beach on a seasonal basis. The four seasonal profiles plotted on Figure I-10 illustrate the migration of berms in the high-tide portion of the beach and the presence of intermittent swash bars in the low-tide section (see photo in Figure I-11). Apparently, the stable central platform is a zone where finer clasts bypass over the coarse-grained surficial armor without disrupting it.

Sleepy Bay

Introduction. This gravel beach is located at the head of Sleepy Bay, an embayment on the north end of Latouche Island. It is similar to Point Helen in overall morphology, but the grain size of the mobile sediment is

* We assumed that the sediments designated P had a 20% matrix of granule/sand.

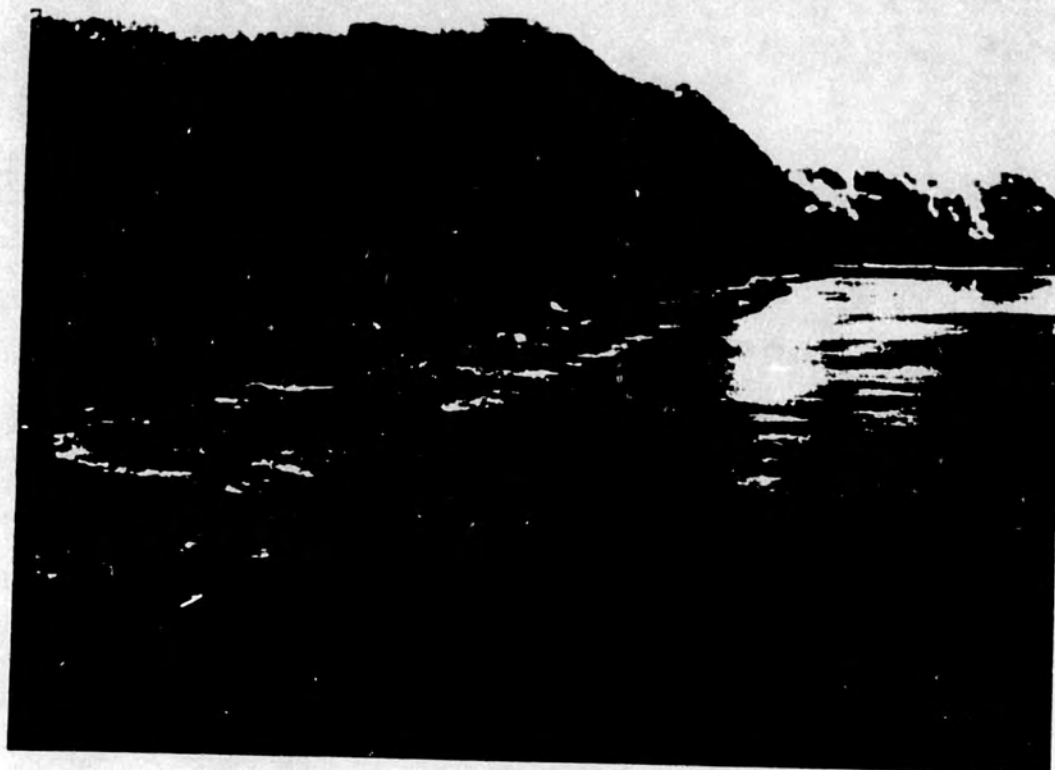


Figure I-11. Point Helen at low tide on 5 January, 1990. Note the presence of gravel swash bars in the intertidal zone that were obviously migrating in a southerly direction.

somewhat smaller because of its more sheltered location. The area of interest is bisected by a small, anadromous stream that is constantly shifting position as it builds a small delta. Due to uplift in the area on the order of 8-10 feet during the 1964 earthquake, the beach has not completely readjusted to an equilibrium profile. The specific area used as the candidate beach is shown in Figure I-12. This area includes NOAA's station N-18 and Exxon's station AP-13.

The Beach Profile. As shown on the map in Figure I-13, the NOAA team surveyed three profiles at the study site in May 1990. In addition, NOAA's permanent station N-18 was surveyed seven times between September 1989 and May 1990.

Exxon and ADEC also had a number of permanent profile sites in this area; thus, the dynamic changes of the profile of the beaches at this site are well documented.

NOAA's profile N-18, illustrated in Figures I-14 and I-15, serves as a basis for the following description:

1) High-Tide Berms

The upper $\pm 10\text{m}$ of the profile typically consists of a number of storm and spring-tide berms, composed mostly of pebbles and cobbles. The berms at the top of the beach were deposited after the beach was flattened during a period of large waves and high tides in October 1989.

2) Stable Central Ramp

Just as at Point Helen, the central portion of the profile has shown little change over the fall-winter-spring interval of 1989-90, except for possibly a small degree of overall lowering. Mixtures of cobbles and pebbles, oriented in bands parallel with the shoreline, cover the entire surface of this zone.

3) Low-Tide Bars

Swash bars showing a range in grain size from sand to cobbles have been observed on the lower portion of the beaches in this area during both the Exxon and NOAA surveys. Many of these bars were associated with the delta at the stream mouth.

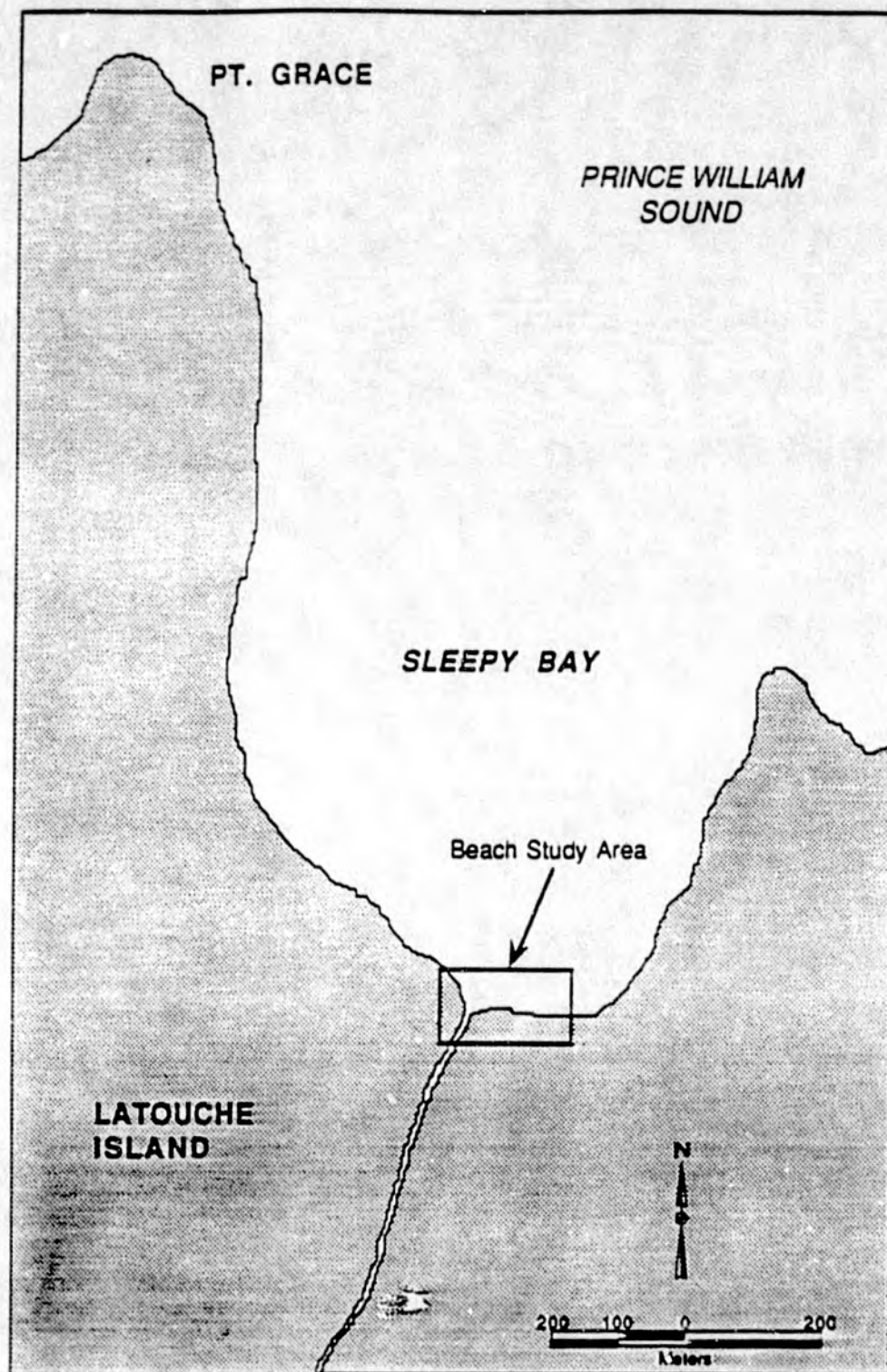


Figure I-12. Map of Sleepy Bay showing the location of the specific section of Sleepy Bay used as a candidate beach for this analysis.

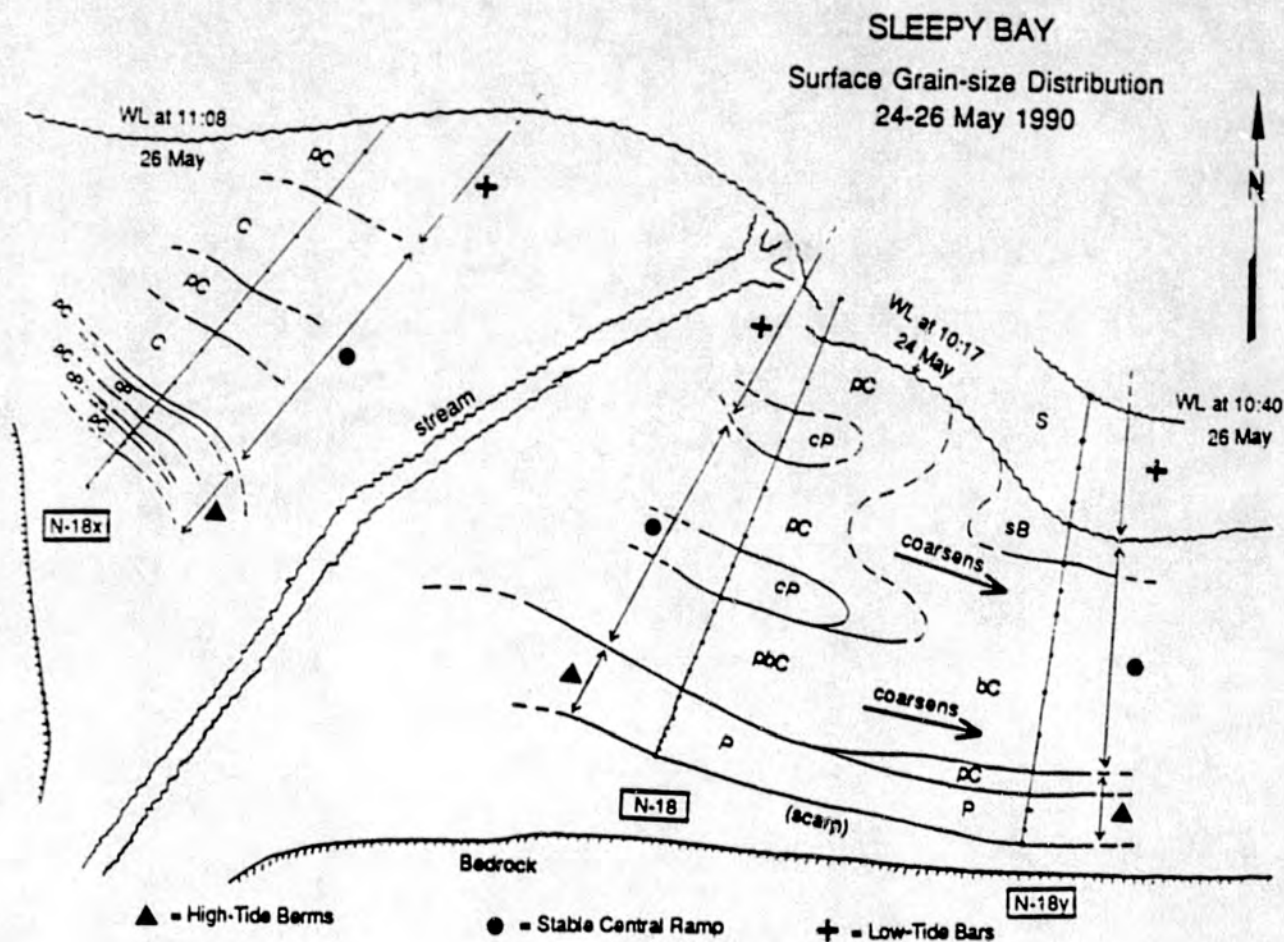


Figure I-13. Surface sediment distribution map at the head of Sleepy Bay on 24-26 May, 1990. Map is based on grain size estimates made along three beach profiles established by NOAA (N-18; N-18x; N-18y). The sediments are mostly parallel bands of different mixtures of pebbles and cobbles. The river mouth migrates constantly, thus these patterns will change in the future.

[illegible]

33

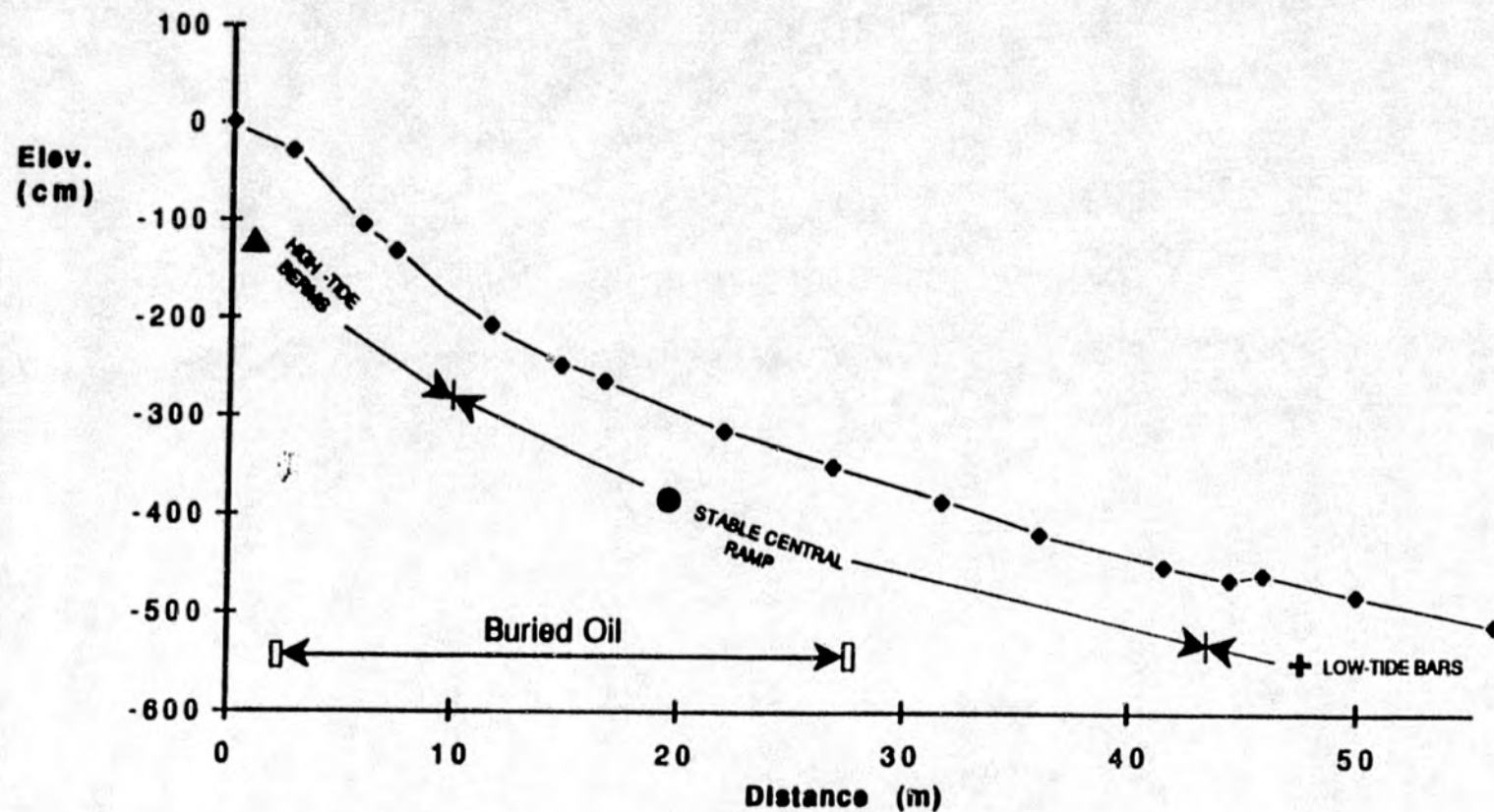


Figure I-15. Plot of NOAA's beach profile N-18 as it appeared on 1 February, 1990. During the fall-winter-spring of 1989-1990, the upper part of the profile was host to multiple migrating berms, the central part was relatively stable, and the lower part contained swash bars from time to time, some of which were associated with the river delta.

Composition and Grain Size of Beach Clasts. The sediments on the beaches at the head of Sleepy Bay are derived from two sources: (1) the rocky headlands located within and to either side of the bay; and (2) the stream and its delta. The coarse clasts, which are quite hard and resistant to breakage, have the same wide variety of composition that is present at the Point Helen site. Dark-colored metamorphosed sandstone, shale, and basaltic lava are common, as well as several other rock types.

A map of the distribution of grain size of the surficial beach materials at the head of Sleepy Bay is presented in Figure I-13. Note that most of the surficial sediments at the site are composed of pebbles and cobbles. Boulders are rare, except to the east of profile N-18y. A plot of 26 grain size estimates for the surficial sediments along NOAA's profile N-18 is given on the ternary diagram in Figure I-16.

Over 30 trenches have been dug by the NOAA team at this site. Two typical trenches from the oiled sector that were dug on 24 May 1990 are shown in Figure I-17. Armoring is relatively poorly developed at this site compared to many others in the Sound, the sediments at depth being only slightly finer than the surface layer (except for the absence of boulders at depth). This probably is a function of the finer-grained, more mobile character of the sediment. However, this beach sediment was mixed significantly during cleanup last summer, and it is possible that there has not been enough time for the armoring process to have matured.

If rock washing were to be carried out at this site, the focus would be on the buried oil, which is located between 3-28m along the profile. The surface layer of sediments in that zone average: 9% B; 40% C; 49% P; and 2% G/S. However, the subsurface sediments described in the trenches are somewhat finer: 1% B; 26% C; and 73% P. If one assumes that in the rock washing process five times more material would be derived from the subsurface than from the surface, the sediments to be washed at Sleepy Bay would have the following grain size:

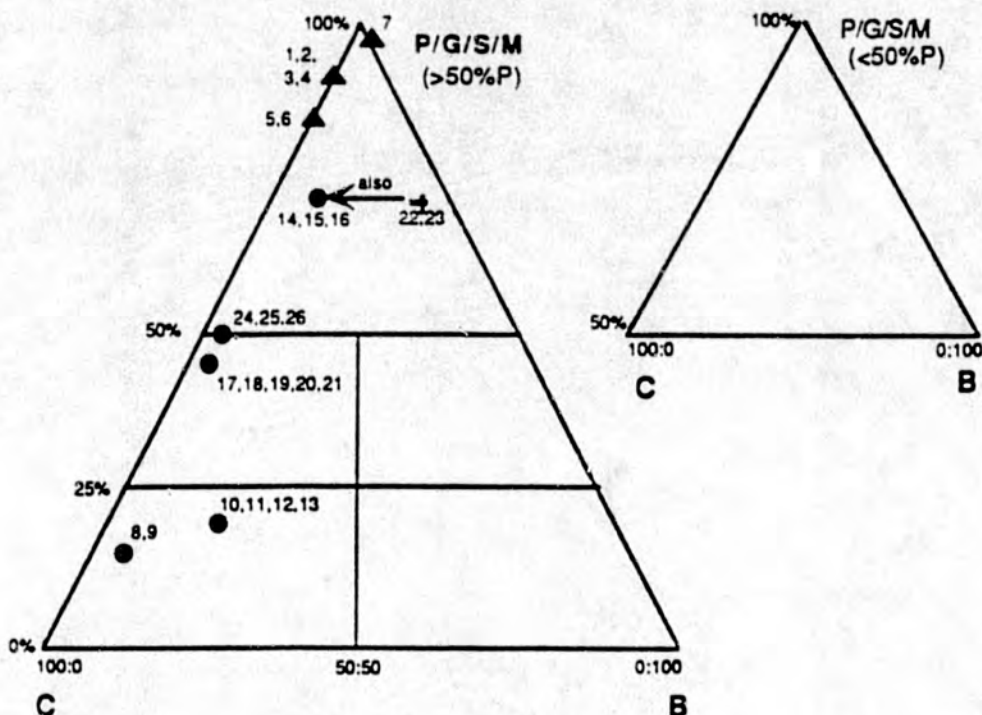
ZONAL GRAIN SIZE DESCRIPTOR

PROFILE: N-18

LOCATION: Sleepy Bay

DATE: 24 MAY '90

X PROFILE STATIONS -OR-
— TRENCH DESCRIPTIONS



NOTES FOR VERBAL DESCRIPTION:

▲: Pebble berm.

●: Pebbly cobbles alternating with sandy pebbles;
 some boulders, especially higher on ramp.

⇐: Pebbly swash bar over pebbly cobbles.

Figure I-16. Plot of estimates of the grain size of the surface sediments at 26 intervals along NOAA's profile N-18 on 24 May 1990. Note that mixtures of pebbles and cobbles predominate.

SITE N-18

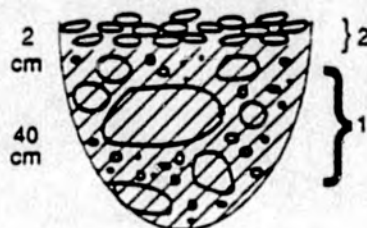
Sleepy Bay, 24 MAY 1990



oil bearing sediments

TRENCH "B"

Photo 31



Ut. 2 70 P, 30 Gr V. discoidal

Ut. 1 5B, 40 C, 40 P, 15 Gr

Ut. 1 Coated with med. brn. mouse, not saturated

Ut. 2 clean

scattered spruce needles in Ut. 1.

TRENCH "C"

Photo 32



Ut. 3 50C, 50P clean

Ut. 2 50P, 40Gr, 10S clean, P's mostly <2cm

Ut. 1 10C, 50P, 40Gr mousse

V. dk. brn. mousse coating in Ut. 1, not saturated

Figure I-17. Description of sediments in two trenches dug on NOAA's profile N-18 on 24 May 1990. See Figure I-14 for location. Surface armoring is not as well developed in these trenches as it is elsewhere in Prince William Sound.

sediments described in the trenches are considerably finer: 1% B; 58% C; and 41% P. If one assumes that in the rock washing process five times more material would be derived from the subsurface than from the surface, the sediments to be washed at Point Helen would have the following grain size:

<u>Sediment Type</u>	<u>Percent</u>	<u>Average Size</u>
Boulders	2	40cm
Cobbles	61	13cm
Pebbles	30	2cm
Granule/Sand*	7	3mm

Energy Level and Beach Dynamics. - This beach is exposed to the east, the direction from which the dominant winds blew during storms in the fall-winter-spring period of 1989-90, according to data gathered at NOAA's meteorological stations at Lone Tree and Danger islands. The effective fetch distance ranges from 15-20 km in a due easterly direction up to 45-50 km to the NNE. No seasonal measurements of wave or current conditions are available for the site.

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Sleepy Bay

Introduction. This gravel beach is located at the head of Sleepy Bay, an embayment on the north end of Latouche Island. It is similar to Point Helen in overall morphology, but the grain size of the mobile sediment is

* We assumed that the sediments designated P had a 20% matrix of granule/sand.

I.C.3. SEDIMENT OIL CONTENT AND COMPOSITION OF CANDIDATE BEACHES

Point Helen - Oil Content

There are several sources of data on the oil content of sediments along Point Helen. NOAA has a monitoring station about 1,500 meters north of the point. This station was occupied monthly from September 1989 to February 1990, and in May 1990. During these surveys, 37 sediment samples were collected and analyzed for TPH by both weight and volume. The measured concentrations of oil in these samples should be reviewed with caution because the substrate is very heterogeneous in both size and oil content. The samples represent only the finer-grained components since only sediment pebble-sized and smaller can fit into the sampling containers. Because the mass of these large-grained sediments is so large compared to their surface area, the traditional measure of oil contamination in milligrams per kilogram (mg/kg) by weight is not very meaningful. Measuring the oil content of the sediments by volume is a better approach, but it still suffers from disturbance of the sediment packing (thus volume) and poor representation of the entire substrate.

Figures I-18 through I-20 show the sediment analyses for samples collected along the NOAA monitoring beach profile at Point Helen for each month. The values shown are TPH by weight. The values shown on the profile line are surface samples; the samples shown below the line are placed at the depth of sampling. Although there are wide variations, several distinct trends are discernable. The oil was heaviest along the upper one-third of the intertidal zone, covering a width of about 12m. The remainder of the intertidal zone had concentrations in the 100-200 mg/kg range. The oil content of the surface sediments, down to about 30cm, was significantly reduced after September, with all samples except one below 300 mg/kg. Visually, the surface sediments at Point Helen appeared cleaner after the first few fall storms. Surface oil remains as a stain on the cobbles and boulders with heavier coating on the back side of boulders sheltered from waves.

The degree of oil contamination of the subsurface sediments has also visually improved. In the fall, sediments in trenches were described as

Station N-1

Δ Oil Conc. (mg/kg)

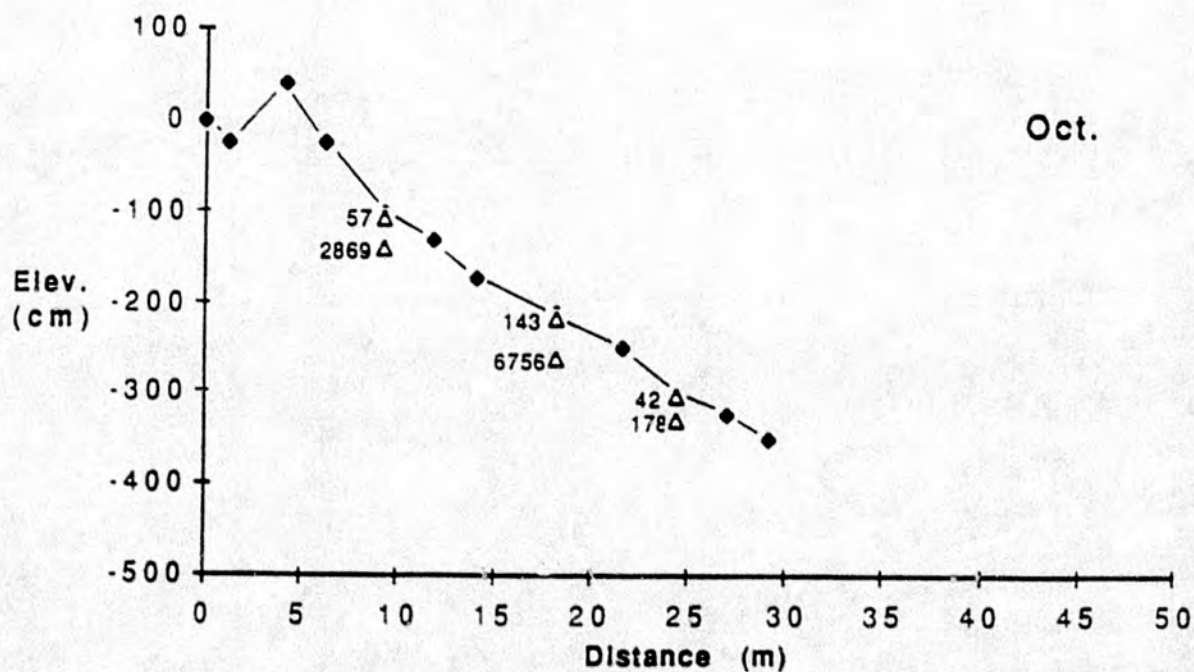
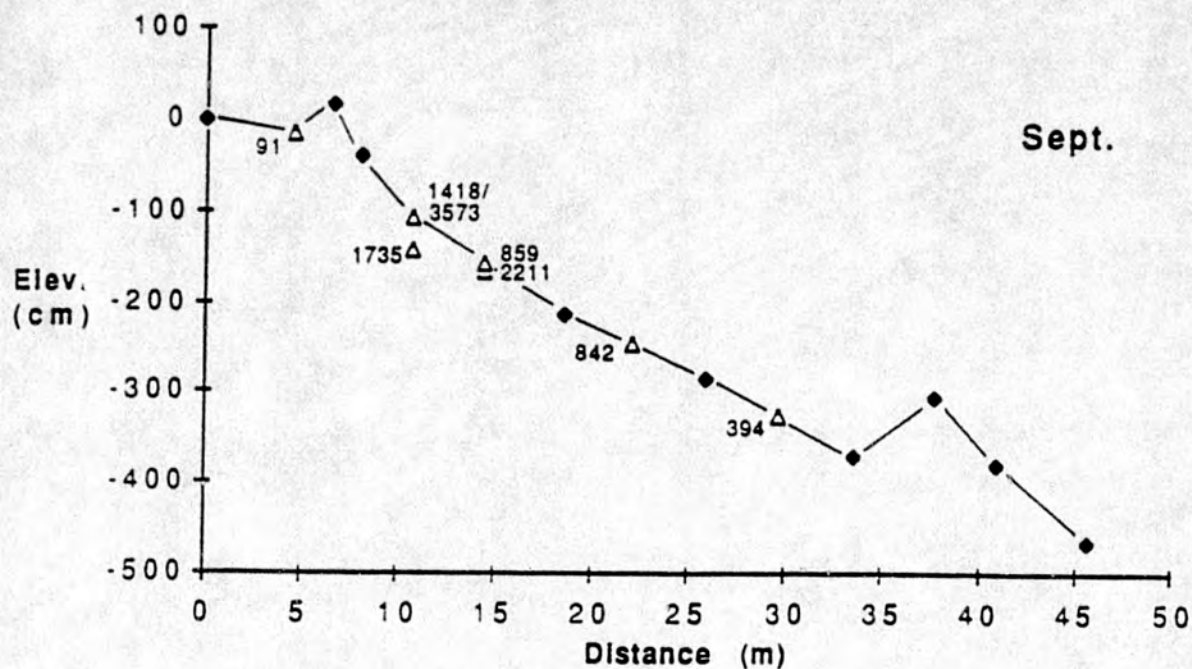


Figure I-18. Plots of the shoreline profile for Sept. and Oct., 1989, at NOAA Station N-1, Point Helen. Oil concentrations at the depths are shown in mg/kg.

Station N-1

Δ Oil Conc. (mg/kg)

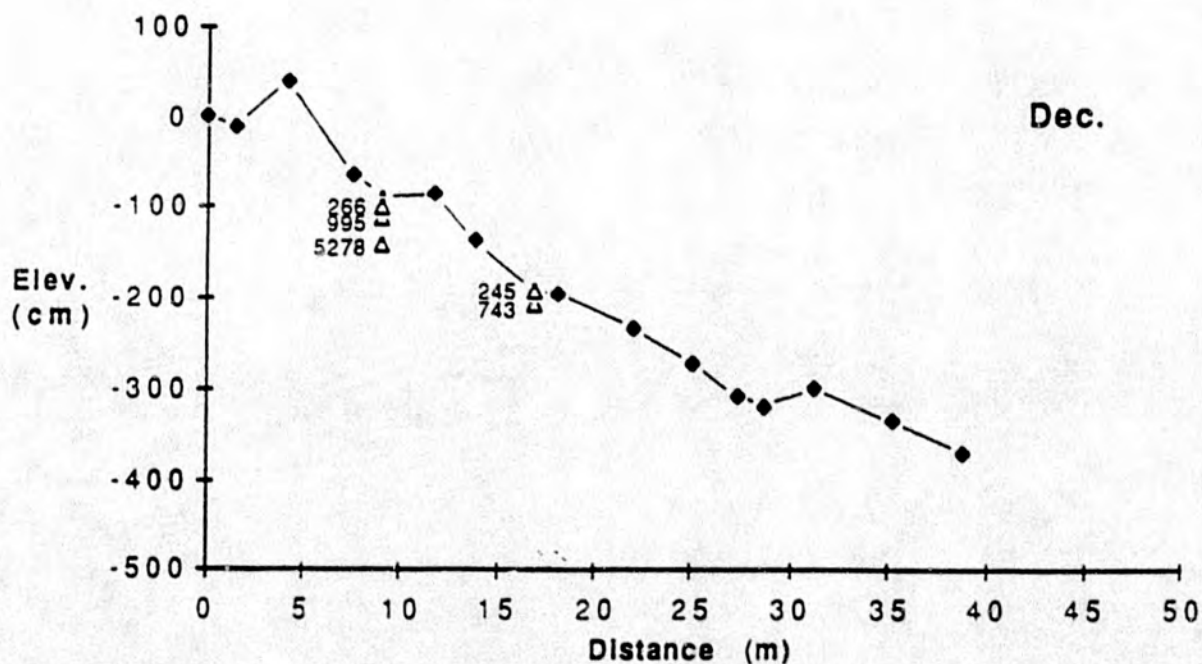
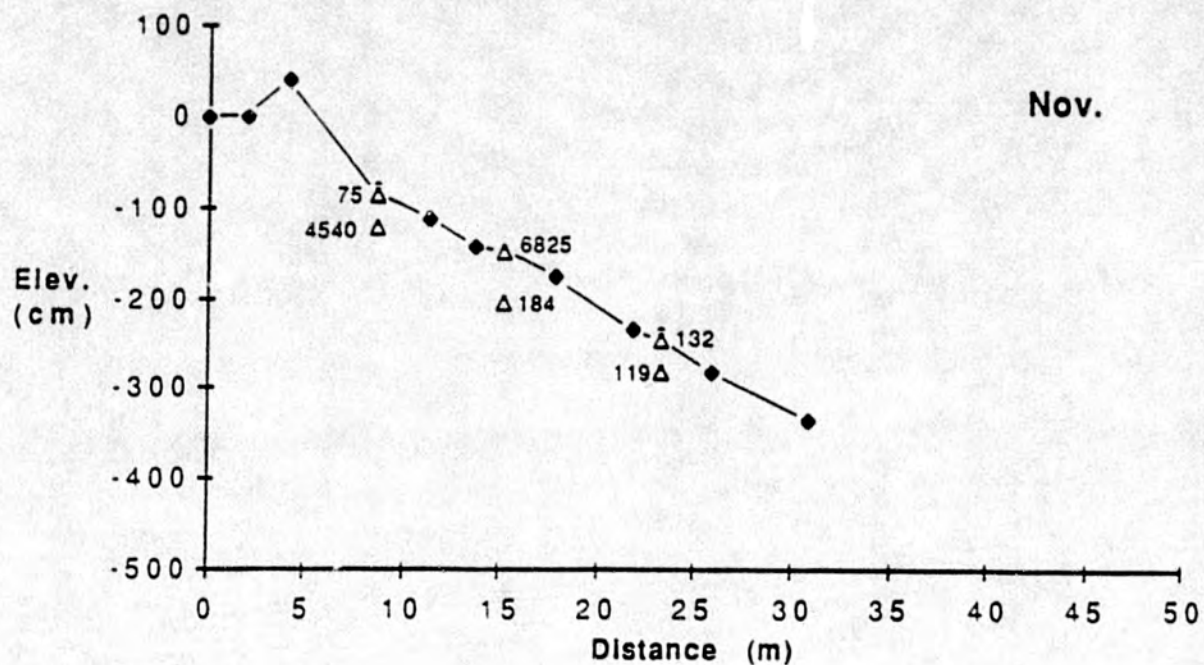


Figure I-19. Plots of the shoreline profile for Nov. and Dec., 1989, at NOAA Station N-1, Point Helen. Oil concentrations at the depths are shown in mg/kg.

Station N-1

Δ Oil Conc. (mg/kg)

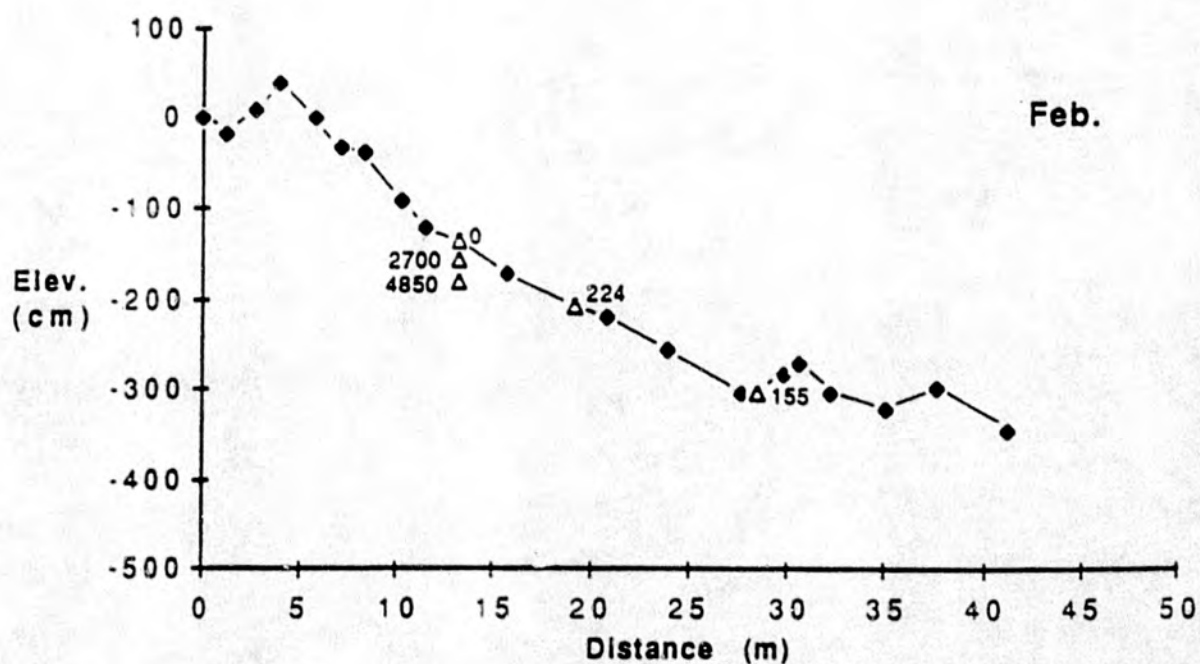
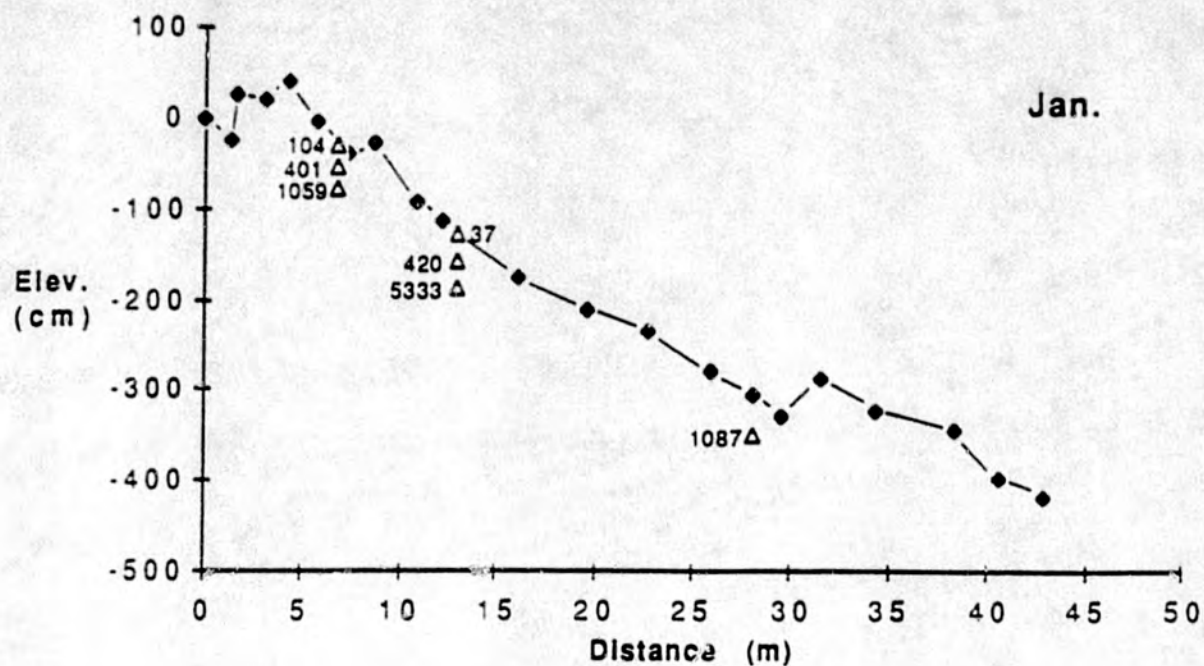


Figure I-20. Plots of the shoreline profile for Jan. and Feb., 1990, at NOAA Station N-1, Point Helen. Oil concentrations at the depths are shown in mg/kg.

heavily coated with liquid, black oil which floated on the water table. By spring, the oil was described as light to moderate. The average oil content of samples collected at depths greater than 30cm from the upper third of the beach ranged between 2,000 and 3,500 mg/kg, with no distinct trend over time. Large variations in the oil content of subsurface sediments are expected, so it will be difficult to rely upon analytical measures. Visual observations are very important, and visually there has been a significant reduction in the amount of oil in subsurface sediments, even below 30cm.

An estimate of the volume of oil in the candidate beach at Point Helen is based on the following assumptions:

- 1) Width of subsurface oil = 12m, based on a maximum extent of >1,000 ppm by weight in any samples collected from NOAA's station between September 1989 and February 1990.
- 2) Depth of subsurface oil = 100cm (average maximum)
50cm (average at the edges)

Top 20cm are "clean."

- 3) Oil content of subsurface sediments is determined from the following percent oil by volume measurements of NOAA samples over the winter:

<u>Month</u>	<u>Maximum %</u>	<u>Mean %</u>
Feb	1.1	0.85
Jan	1.1	0.4
Dec	1.0	0.5
Nov	0.78	0.78
Oct	<u>1.1</u>	<u>0.82</u>
Mean	1.0	0.67 = 0.5%

These values are for the smaller components of the beach sediment (granule to pebble). According to grain-size descriptions of trenches at N-1 at Point Helen in May 1990, the subsurface sediments are about 50 percent cobble or greater and 50 percent pebble/granule/sand. It is assumed that the volumetric amount of oil on a cobble/boulder is negligible.

The cross-sectional area of oiled sediments is calculated as:

$$\begin{array}{rcl} 12 \text{ m} \times 1 \text{ m} & = & 12 \text{ m}^2 \\ & - & 2.4 \text{ m}^2 \quad (\text{reduction due to the clean top 20 cm}) \\ & - & \underline{3.0 \text{ m}^2} \quad (\text{due to thinner depth of oil at edges}) \\ & = & 6.6 \text{ m}^2 \quad \text{oiled sediment per linear m of beach} \end{array}$$

The oil volume per linear meter of beach is calculated as:

$$\begin{array}{l} 6.6 \text{ m}^2 \times 0.5\% \text{ oil by volume} \times 1 \text{ m beach length} \times 0.5 (\% < \text{cobble}) \\ = 0.016 \text{ m}^3 \quad \text{or} \quad 4.3 \text{ gallons per linear meter of beach} \end{array}$$

ADEC performed similar calculations based on an oiled zone at 30-120cm depth and estimated 6.2 gallons per meter of beach.

The area of Point Helen selected for review is 300m long, thus that shoreline is estimated to contain 1,290 gallons of oil. Assuming that the returned sediments still contain 800 ppm oil by weight (or an estimated 0.1 percent by volume), washing will remove approximately 1,030 gallons from this 300m stretch of shoreline. For all the area of Point Helen which has subsurface oil (an estimated 2,500m length), washing would remove an estimated 8,700 gallons from the subsurface sediments.

Sleepy Bay - Oil Content

There are three sources of data on subsurface oil volume at Sleepy Bay: NOAA's winter monitoring program; Exxon's March 1990 survey; and a June 1990 survey by Exxon. The oil distribution on the surface and in the subsurface is highly variable in Sleepy Bay, thus there were different results for each of the programs monitoring the degree and changes in oiled sediments. NOAA's monitoring station is located 50m to the east of the major stream. It has been occupied monthly between September 1989 and February 1990 and again in May 1990. A total of 43 sediment samples have been analyzed for TPH from this station, and the results are shown in Figures I-21 through I-23. The zone of subsurface oil is about 25m, wider than Point Helen. The oil concentrations in the surface sediments have been reduced from about 1,000 ppm in the fall to 100 ppm in the late winter.

Station N-18

Δ Oil Conc. (mg/kg)

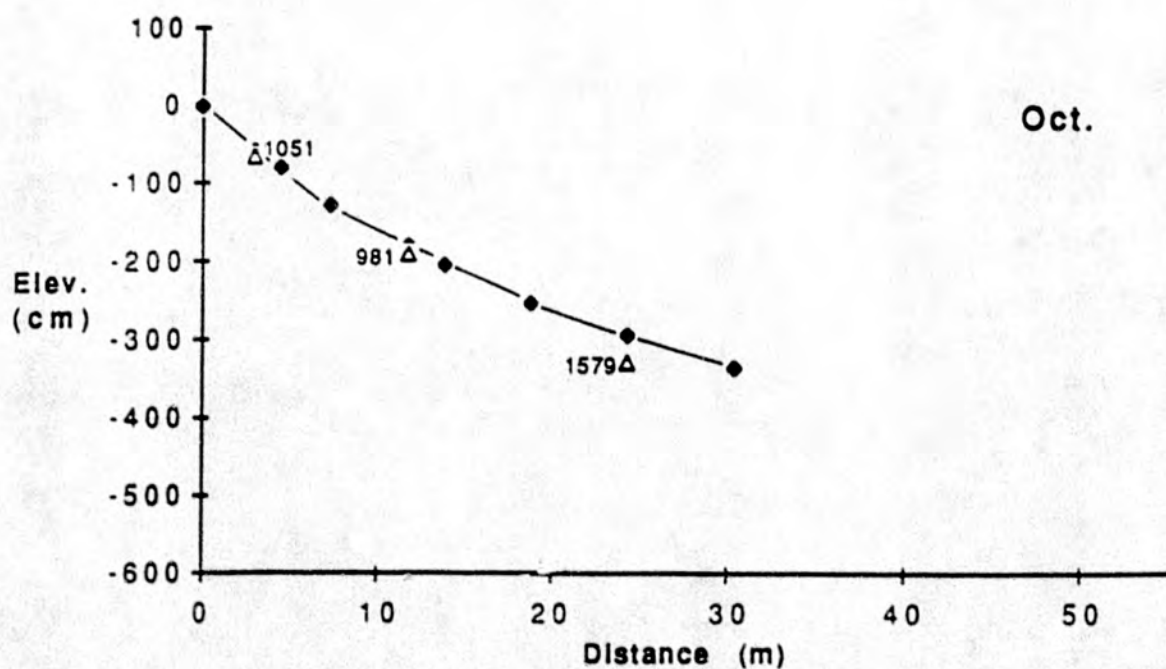
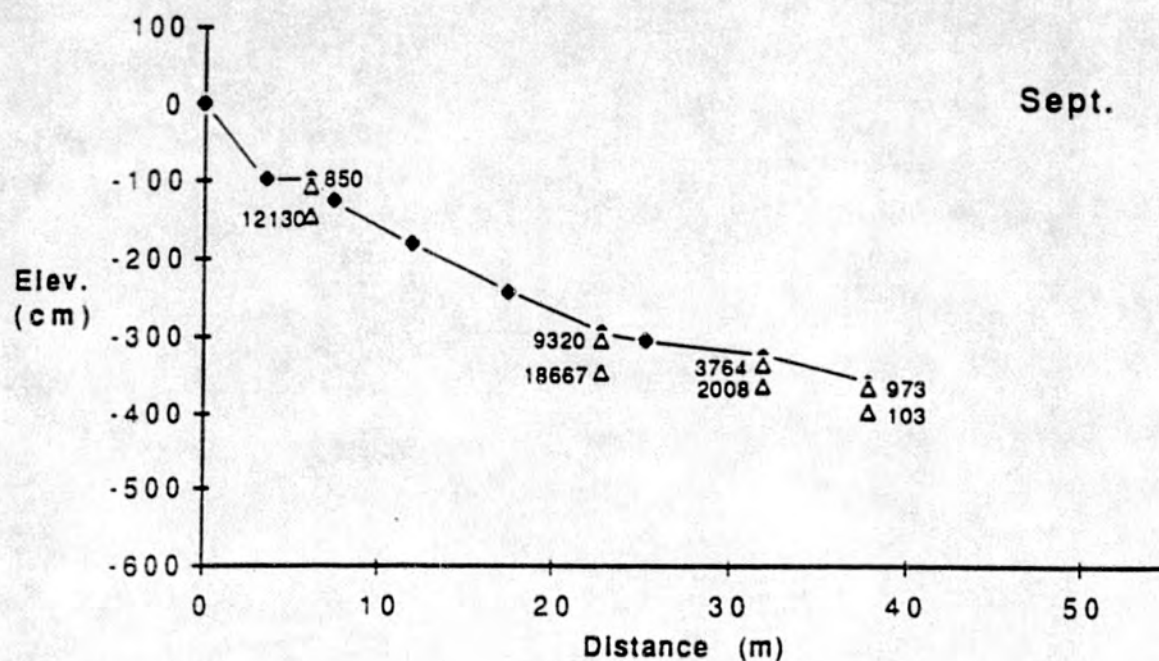


Figure I-21. Plots of the shoreline profile for Sept. and Oct., 1989, at NOAA Station N-18, Sleepy Bay. Oil concentrations at the depths are shown in mg/kg.

Station N-18

Δ Oil Conc. (mg/kg)

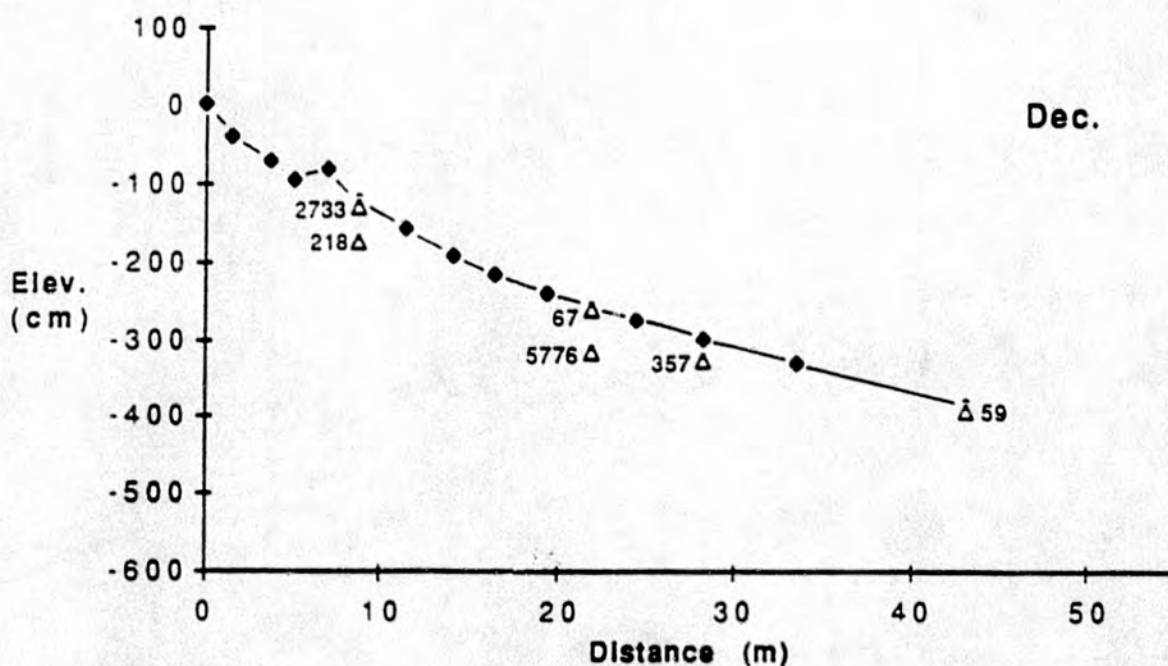
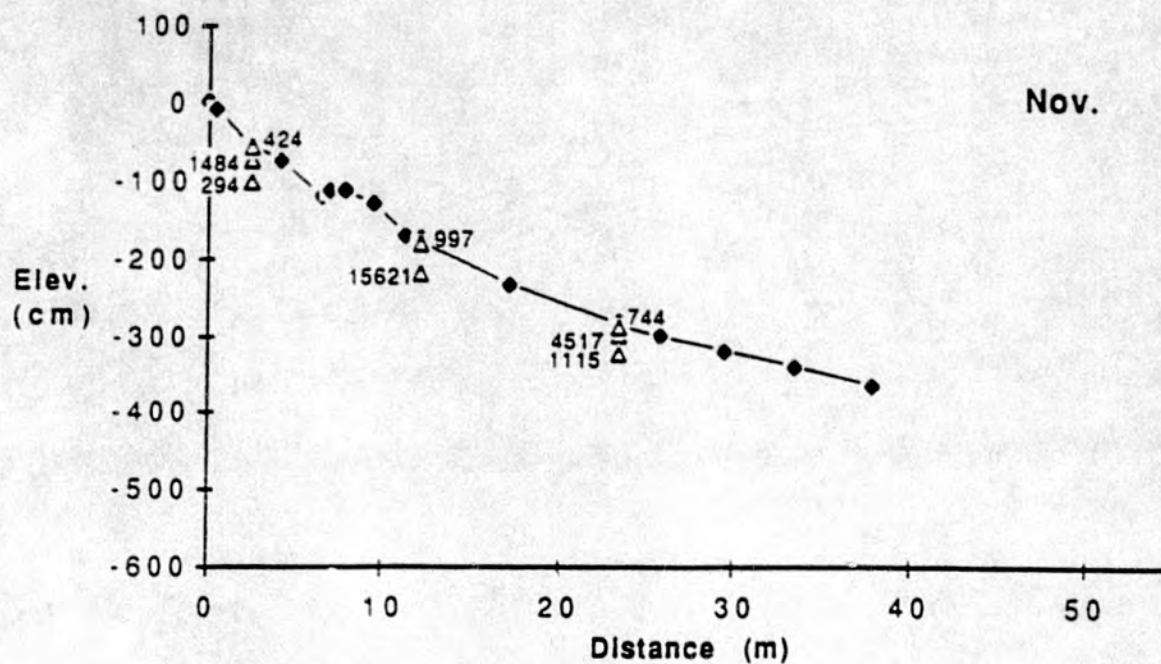


Figure I-22. Plots of the shoreline profile for Nov. and Dec., 1989, at NOAA Station N-18, Sleepy Bay. Oil concentrations at the depths are shown in mg/kg.

Station N-18

Δ Oil Conc. (mg/kg)

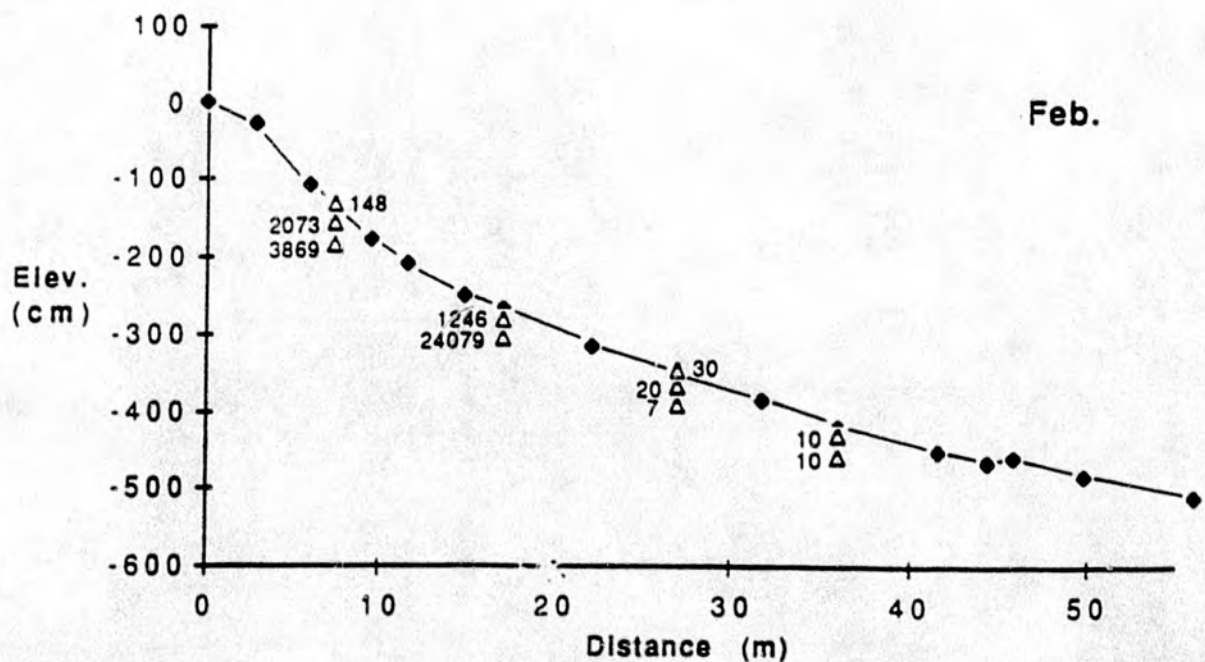
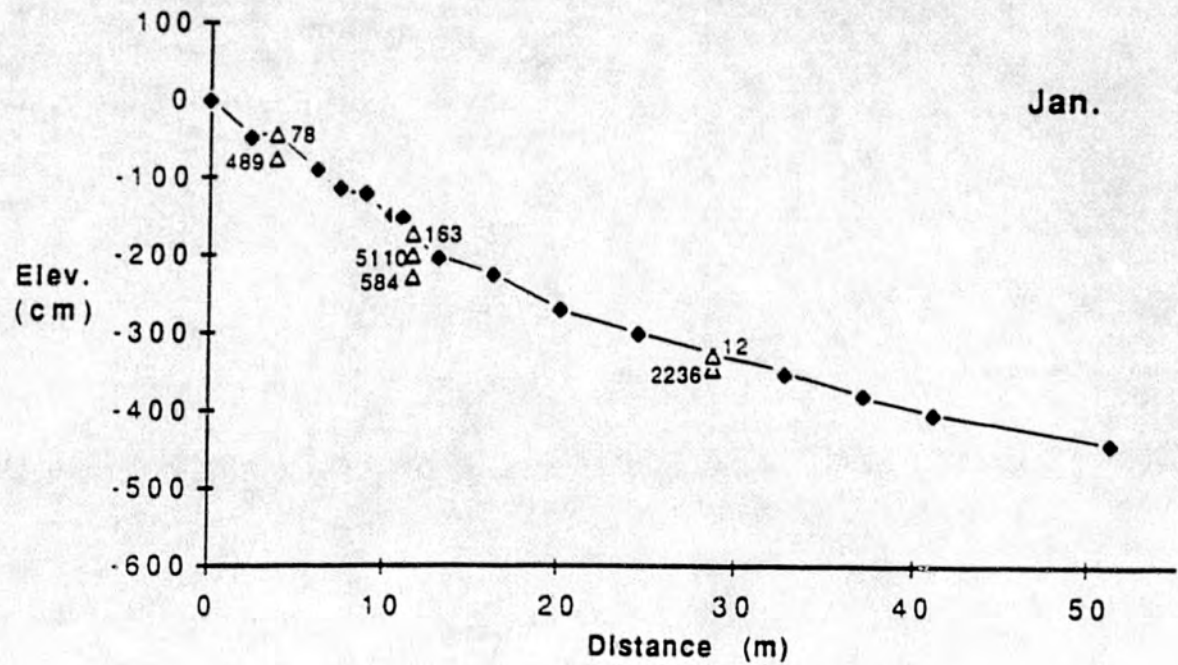


Figure I-23. Plots of the shoreline profile for Jan. and Feb., 1990, at NOAA Station N-18, Sleepy Bay. Oil concentrations at the depths are shown in mg/kg.

However, there are wide variations in oil distribution with depth and over time, as a function of sediment reworking. The initial heavy oiling of sediments at the high-tide berm (over 12,000 mg/kg in September) was greatly reduced as the berm (composed of pebble-sized sediments) was eroded, reformed, and migrated with changing neap to spring tides. The central part of the beach had high subsurface oil concentrations throughout the monitoring period, ranging from 5,800 to 24,000 mg/kg, with the natural variation masking any temporal trends. In fact, the highest value measured was for a February 1990 sample from the upper part of the central platform. The rest of the intertidal zone has relatively low levels of oil contamination, with concentrations in February of 50 mg/kg or less.

An estimate of the volume of oil in the candidate beach at Sleepy Bay using NOAA data is based on the following assumptions:

- 1) Width of subsurface oil = 25m
- 2) Depth of subsurface oil = 60cm (average maximum)
30cm (average at the edges)

Top 20cm are "clean."

- 3) Oil content of subsurface sediments is determined from the following percent oil by volume measurements of NOAA samples over the winter:

<u>Month</u>	<u>Maximum %</u>	<u>Mean %</u>
Feb	4.5	1.4
Jan	0.7	0.4
Dec	1.0	0.4
Nov	2.6	1.0
Oct	0.9	0.3
Sept	3.3	1.4
Mean	2.2	0.8

These values are for the smaller components of the beach sediment (granule to pebble). According to grain-size descriptions of trenches in the candidate beach area of Sleepy Bay in May 1990, the subsurface sediments

are about 25 percent cobble or greater and 75 percent pebble/granule/sand. It is assumed that the volumetric amount of oil on a cobble/boulder is negligible.

The cross-sectional area of oiled sediments at Sleepy Bay is calculated as:

$$25 \text{ m} \times 0.6 \text{ m} = 15 \text{ m}^2$$

$$-5 \text{ m}^2 \text{ (reduction due to the clean top 20 cm)}$$

$$-3.75 \text{ m}^2 \text{ (due to thinner depth of oil at edges)}$$

$$6.25 \text{ m}^2 \text{ oiled sediment per linear m of beach}$$

The oil volume per linear meter of beach is calculated as:

$$6.25 \text{ m}^2 \times 0.8\% \text{ oil by volume} \times 1 \text{ m beach length} \times 0.75$$

$$(\% < \text{cobble}) =$$

$$0.0375 \text{ m}^3 \quad \text{or} \quad 9.9 \text{ gallons per linear meter of beach}$$

The area of Sleepy Bay selected for review is 300 m long, thus that shoreline is estimated to contain 2,960 gallons of oil, about 2 1/4 times more than the amount estimated for Point Helen. Again, assuming that the returned sediments still contain 800 ppm oil by weight (or an estimated 0.1 percent by volume), washing will remove approximately 2,600 gallons from this 300m stretch of shoreline.

Exxon survey teams collected thirteen samples from the eastern section of Sleepy Bay in March 1990 and eleven samples in June 1990. Exxon sampled relatively large intervals, such as from 20 to 40cm in their samples. In March, TPH concentrations in the upper 22m of the beach ranged from 234 to 7,254 mg/kg and averaged 2,363 mg/kg. In June, TPH concentrations in the upper zone ranged from 117 to 11,009 mg/kg and averaged 3,415 mg/kg. Using these numbers and the oil thicknesses measured in each pit, Exxon calculated oil loading as follows:

March 1990	5.0 gallons of oil/meter of beach
June 1990	6.1 gallons of oil/meter of beach

Chemical Composition of Stranded Oil at the Candidate Beaches

Field investigations and detailed gas chromatograph/mass spectrometer (GC/MS) analyses of representative samples collected during May 1990 field investigations of the candidate beaches (LA-18/19, Sleepy Bay, and KN-405, Point Helen) suggest a diversity in weathering processes (fates) and chemical composition of the stranded oil. Oil spilled into the environment is subject to physical and chemical changes. These changes are generally known as weathering and include physical transport mechanisms and chemical/biological alterations of the spilled oil. When spilled oil is stranded on a beach, these weathering processes continue but are modified by the environment (beach material, tides, wave action, etc.) on which it is stranded. The primary weathering processes include spreading, evaporation, dissolution, dispersion, photochemical oxidation, water-in-oil emulsification, adsorption onto suspended material (particulate and colloidal), biodegradation, and various shoreline interactions. Penetration of the oil into the subsurface of the beach and the fate of that oil is the focus of this investigation.

The detailed chemistry data obtained from the May 1990 investigations have been synthesized and presented to provide an understanding of the composition of the remaining oil. Discrete samples were chosen to reflect the different types of oil identified by visual inspection of the beach. The data are presented as histogram plots comparing the "fresh" EXXON VALDEZ cargo oil to May 1990, samples (e.g., mousse, tar mat, weathered oil residues). It should be noted that each of the compositional histograms (Figures I-24 through I-32) are limited in that they present only the relative abundances of the target compounds, namely the polynuclear aromatic hydrocarbon (PAH) compounds. PAHs represent only a small fraction of the "whole" oil remaining; PAHs comprise less than 1% of the fresh oil. The compounds targeted were chosen because of their relative abundance in the spilled oil, persistence in the environment, and toxicological concerns. The y-axis of the plot represents the concentration of individual target compounds in the sample (including the sediment) and are reported as ng of analyte per mg of sample weight (ppm).

Sleepy Bay. Sleepy Bay contains stranded oil characterized as moderate to heavily weathered on the surface with patches of less

weathered mousse and fresher oil contained within exposed tar mats. The mousse found in Sleepy Bay is characteristically an oil-in-water emulsification which is very stable. Figure I-24 shows a comparison of EXXON VALDEZ cargo oil to mousse collected from the surface at Sleepy Bay 14 months after the spill. The slight differences noted between the spilled oil and the 14-month old mousse represent only part of the chemical changes that have occurred during its formation. The GC/MS analysis indicates evaporative and dissolution loss of the lighter constituents. Only slight preferential degradation was noted, indicating very little microbial degradation has occurred. Mousse in the environment is characteristically a very stable material that is slow to degrade without physical breakup since most of the weathering fates are surface dependant. Microbial and photooxidation of the mousse occurs only on the very surface. The resulting effect is the formation of a hard crust which encapsulates the remaining oil within, thus retarding further degradation. The mousse sample collected at Sleepy Bay did not readily sheen. If the emulsion is broken by physical action or even by elevating the temperature (mousse exposed to the solar radiation will act as a black body), the mousse will sheen.

Tar mats represent another pathway of oil degradation. As the tar mat continues to weather, it will ultimately form an asphalt pavement which is very resistant to continued dispersion and degradation. Both the mousse and tar mat are primarily surface impacts only. The recommended treatment is physical removal; therefore, they are not characteristic of the type of oil which the rock washer is expected to remove. Their inclusion in this study is to provide a comprehensive comparison of the types of oil present at the candidate sites, and for contrast with the subsurface oil. Figure I-25 shows a comparison of fresh EXXON VALDEZ oil to a sample of tar mat. Like the mousse sample shown in Figure I-24, the tar mat has undergone only slight weathering. The fresher oil contained within the tar mat will readily sheen.

An example of surface oil from Sleepy Bay that has been significantly degraded compared to EXXON VALDEZ cargo oil is shown in Figure I-26. The heavily weathered oil has lost all of the lighter constituents, the non-alkylated (parent) and C-1 and C-2 PAH homologs are significantly reduced relative to the more degradation-resistive C-3 and C-4 PAH homologs, and

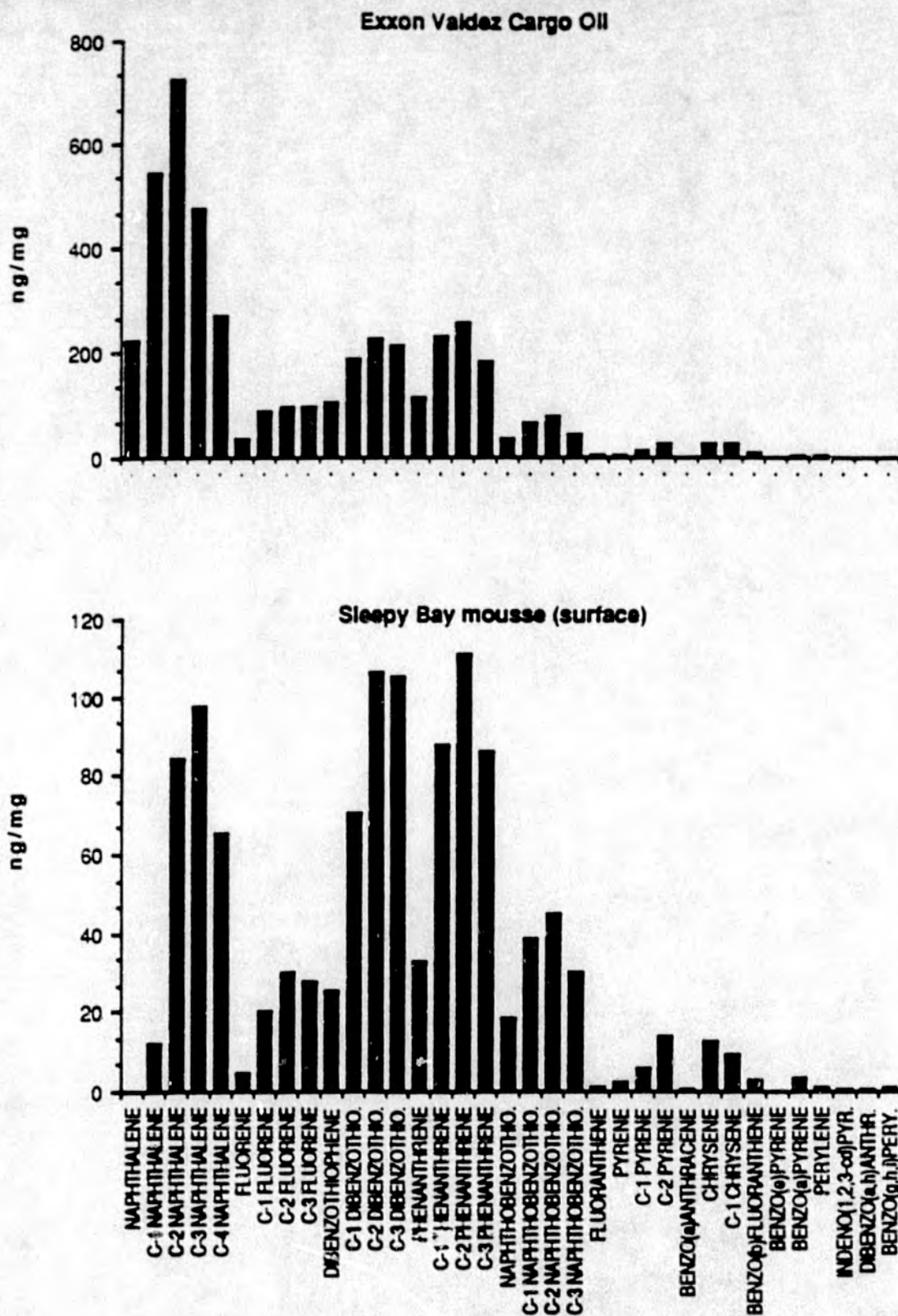


Figure I-24. Comparison of Exxon Valdez cargo oil to mousse collected at Sleepy Bay (May 1990). Note the difference in scale of concentration between the two plots.

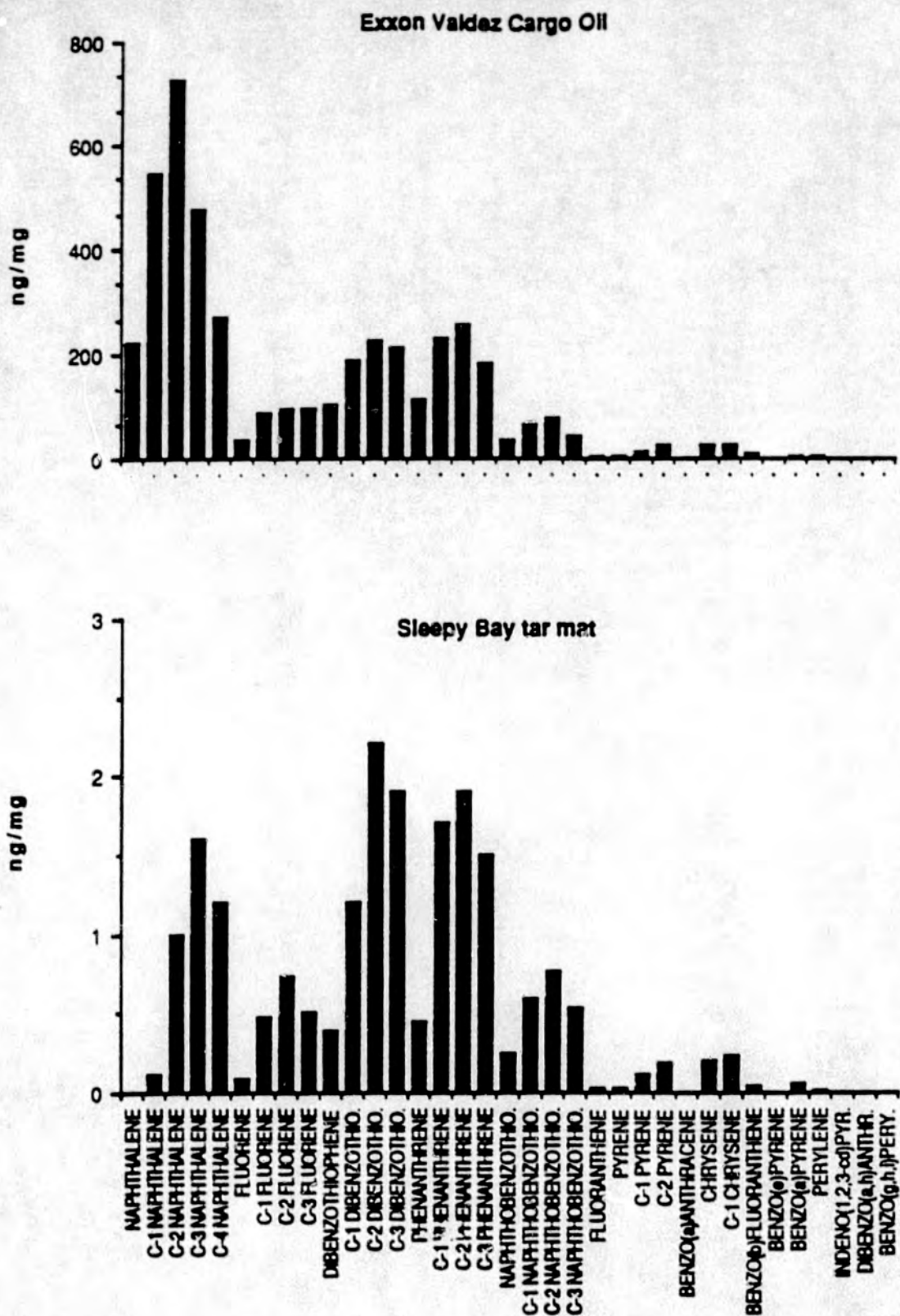


Figure I-25. Comparison of Exxon Valdez cargo oil to oil contained within a tar mat at Sleepy Bay. Note the difference in scale of concentration between the two plots.

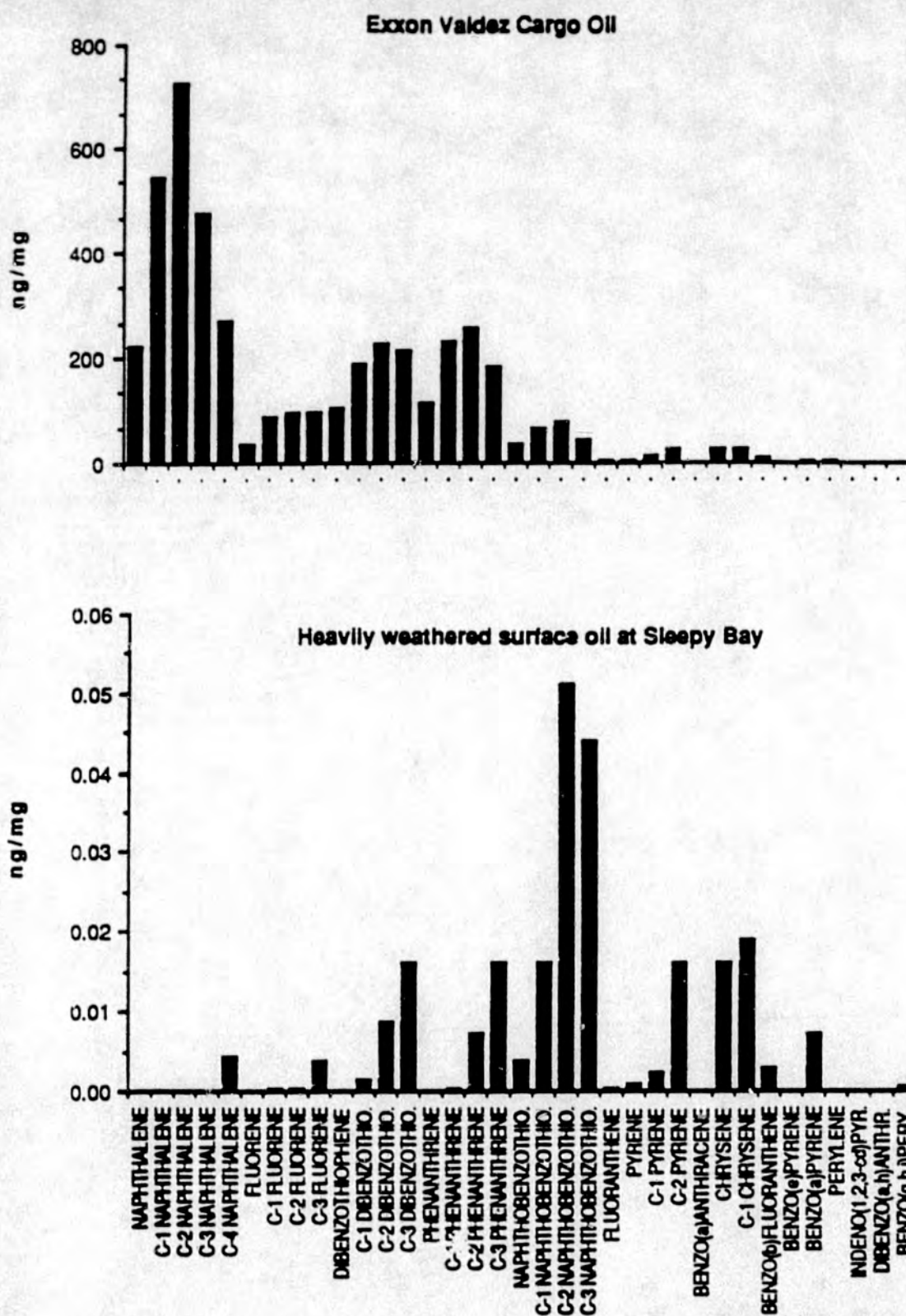


Figure I-26. Comparison of Exxon Valdez cargo oil to a surface sample from Sleepy Bay that is heavily weathered. Note the difference in scale of concentration between the two plots.

the sulfur heterocycle compounds generally show less reduction compared to PAHs with similar molecular weights (e.g., the C-3 dibenzothiophenes, MW=226, are slower to degrade than the C-3 phenanthrenes, MW=220). These changes are consistent with normal degradation in the environment and reflect loss of individual constituents by dissolution and evaporation of the lower molecular weight and more water-soluble compounds in addition to preferential degradation by microbial processes. The sulfur heterocycles (dibenzothiophenes and naphthobenzothiophenes) are becoming more predominant in the target compound profile; this pattern is suggestive of a resistance to microbial degradation relative to the other target compounds. Oil of this composition will not sheen.

Subsurface oil demonstrates a range of weathering similar to the surface. Based on data collected from the NOAA winter study in Prince William Sound and on field observations in May 1990, the absolute quantity of subsurface oil is generally higher in concentration. The subsurface weathering processes differ relative to the surface. The physical composition of the oil varies from a heavily weathered oil residue with a "peat-like" feel to a fresher oil partially emulsified with water and fine colloidal and particulate material. The subsurface oil penetrated the beach substrate while still a relatively fresh oil, filling in available pore spaces. Through continual interactions with the water column (tidal action, etc.) and exposure to fine sediments, organic colloids, natural surfactants, as well as microbial-mediated oxidation and surfactant action, the oil has become viscous, characteristically more "mousse-like," and less mobile.

Interestingly, the composition of the oil buried under the the spring tide berms at Sleepy Bay at depths to 30cm demonstrates significant weathering and is characteristically dissimilar in appearance to "fresh" crude oil or the surface mousse typically encountered in Prince William Sound and the Gulf of Alaska. This oil does not sheen. The degree of weathering is significant, being characterized as moderately weathered. It would appear that the beach is acting in a fashion analogous to a trickle filter system used for waste water treatment. Snow melt, rain, and tidal activities carry nutrients, bacteria, and detrital material from the upland area and the open bay to the berm where it trickles through the berm sediments which are partially coated with oil. This process is probably

most effective during the late spring and summer months when the temperature is warmer and runoff is greater. The upper intertidal and middle intertidal subsurface oil is characteristically not as weathered as that in the spring berm. Factors which may contribute to the reduced degradation rates in the lower areas noted are the physical distribution of the oil (clumpy and "mousse-like") and higher overall oil concentration in the subsurface sediments, which reduces the effectiveness of natural dispersion and degradation activities since they are primarily active at the surface only. Figures I-27 through I-30 show compositional histograms of the target constituents in the oil monitored for the spring tide berm, and the upper, middle, and lower intertidal zones, respectively. Note the changes relative to reference EXXON VALDEZ cargo oil. Oil of this composition doesn't normally sheen.

Point Helen. Only a limited number of May 1990, samples were analyzed from Point Helen. An upper intertidal zone subsurface sample collected at the NOAA study station, N-1, suggest that significant weathering has occurred (see Figure I-31). Neither of the samples collected at Point Helen generated a sheen. The relative composition was similar to that found in the spring tide berms at Sleepy Bay and Point Helen shown in Figures I-27 and I-32, respectively. PAH concentration data of subsurface oil from the Exxon Winter study show similar degradative changes in composition. These values are included in Table I-2.

Very little attention has been given to the saturate fraction of the stranded oil. All of the subsurface samples analyzed showed marked decreases in the lower molecular weight (less than n-C20) aliphatic compounds with a marked preference for the non-branched relative to the branched hydrocarbons. The isoprenoid hydrocarbons norpristane, pristane, and phytane showed a marked resistance to change as well as did the heavier paraffins (greater than n-C20); this selective preference indicates microbial degradation³ has occurred.

In summary, oil stranded on the candidate beaches can be described as four discrete types: mousse, tar mat, moderate to heavily weathered surface oil residues, and subsurface oil. The composition of the subsurface oil suggests that significant weathering has modified the stranded oil. The current composition of the subsurface oil is moderately weathered and

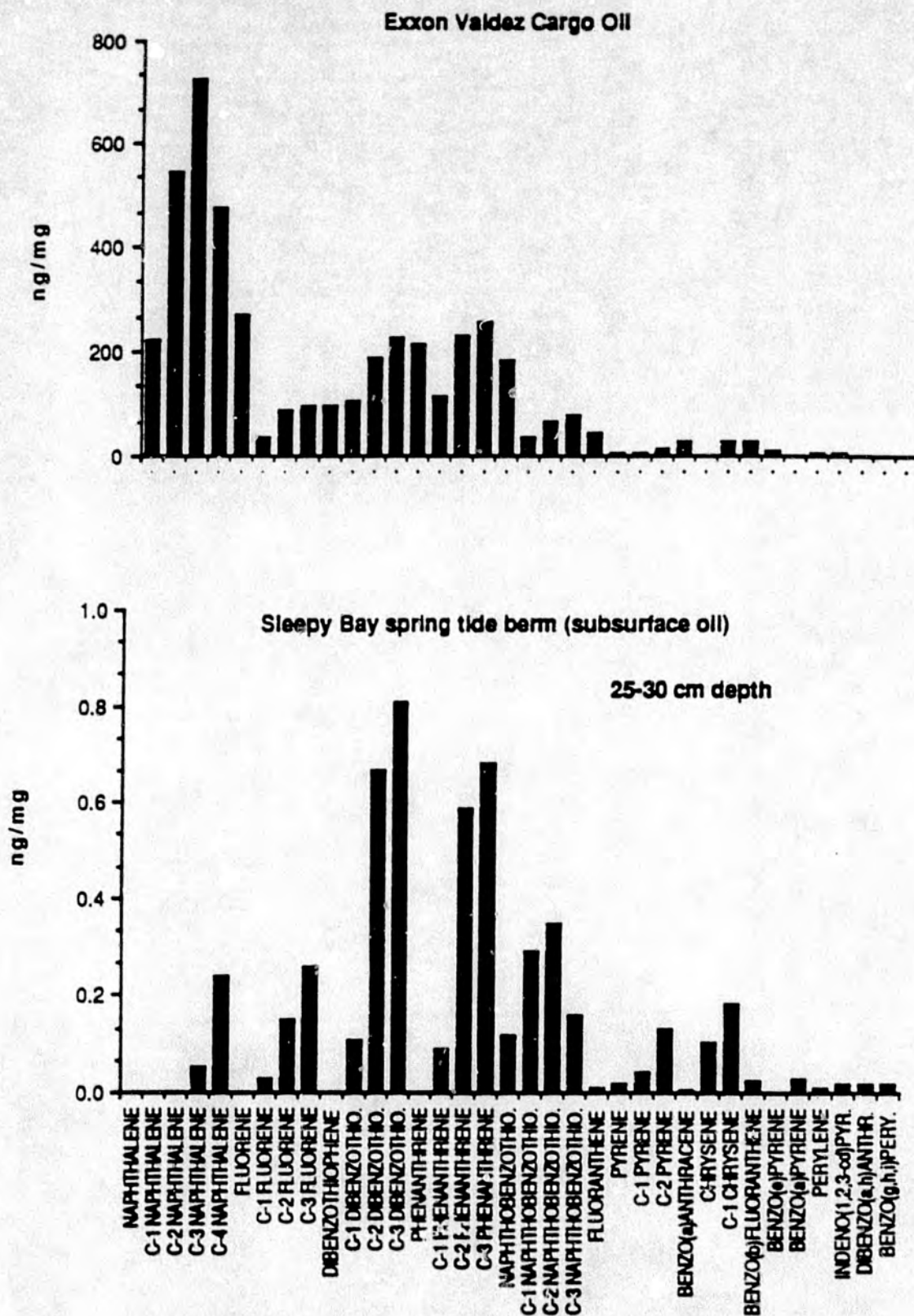


Figure I-27. Comparison of Exxon Valdez cargo oil to subsurface oil buried in the spring tide berm at Sleepy Bay (May 1990). Note the difference in scale of concentration between the two plots.

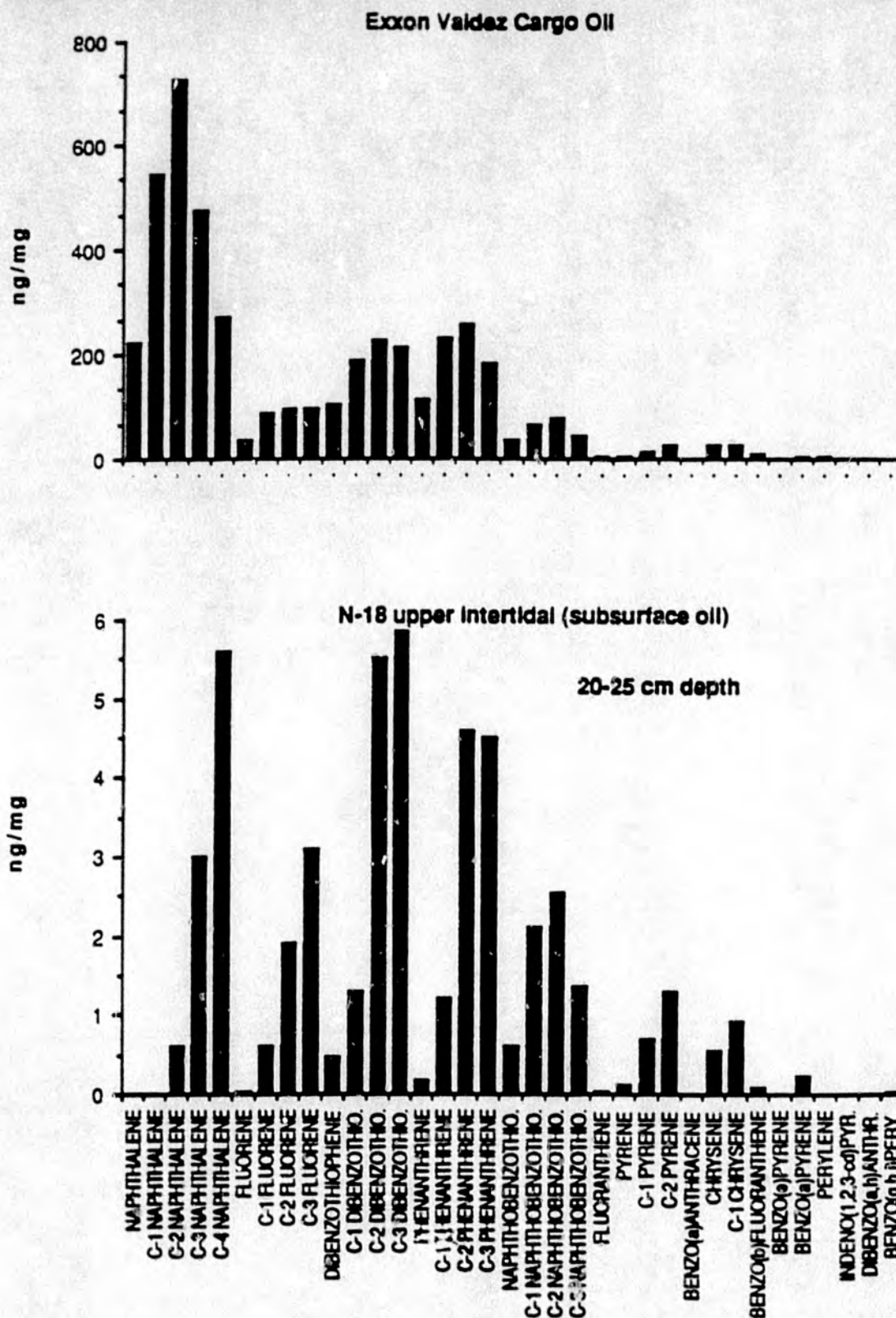


Figure I-28. Comparison of Exxon Valdez cargo oil to subsurface oil of the upper intertidal zone at NOAA study station N-18 (May 1990). Note the difference in scale of concentration between the two plots.

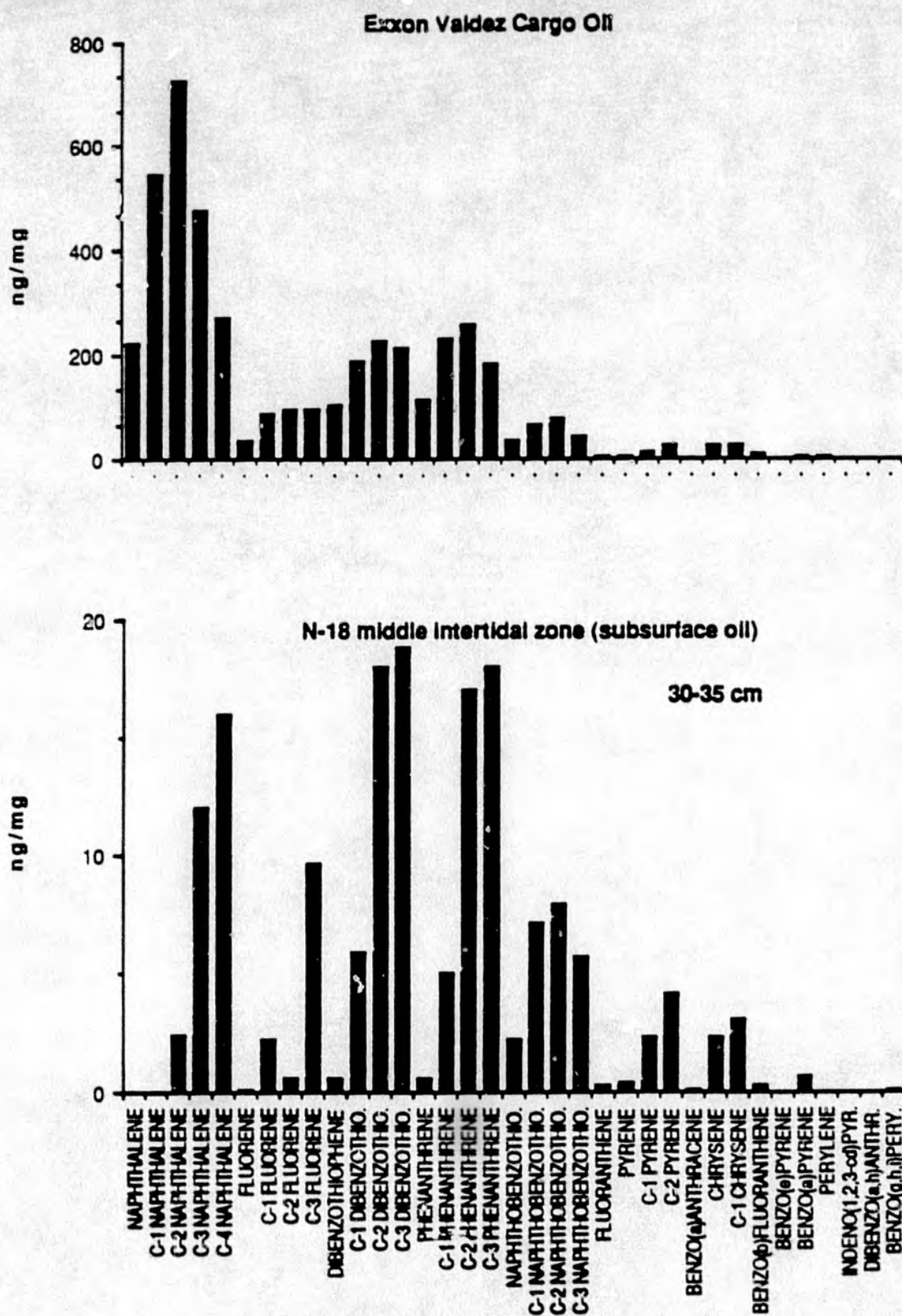


Figure I-29. Comparison of Exxon Valdez cargo oil to subsurface oil of the middle intertidal zone at NOAA study station N-18 (May 1990). Note the differences in scale of concentration between the two plots.

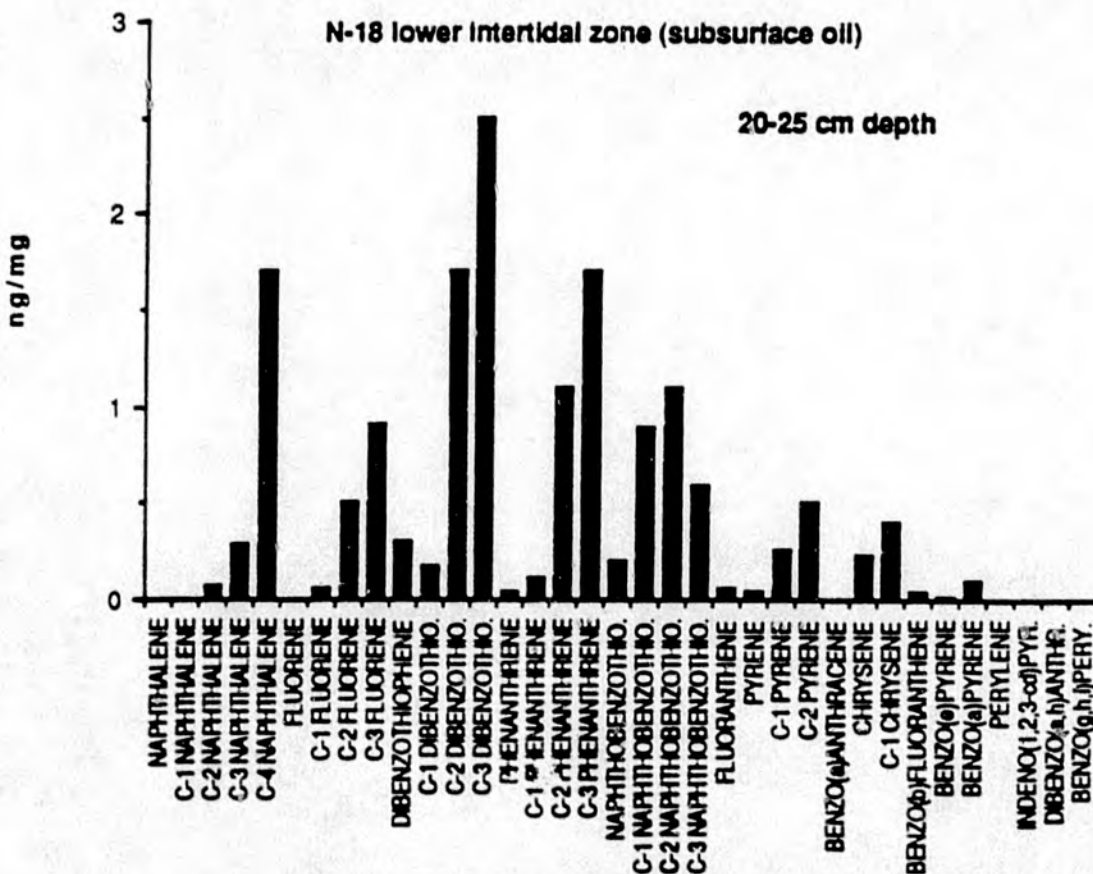


Figure I-30. Comparison of Exxon Valdez cargo oil to subsurface oil of the lower intertidal zone at NOAA study station N-18 (May 1990). Note the difference in scale of concentration between the two plots.

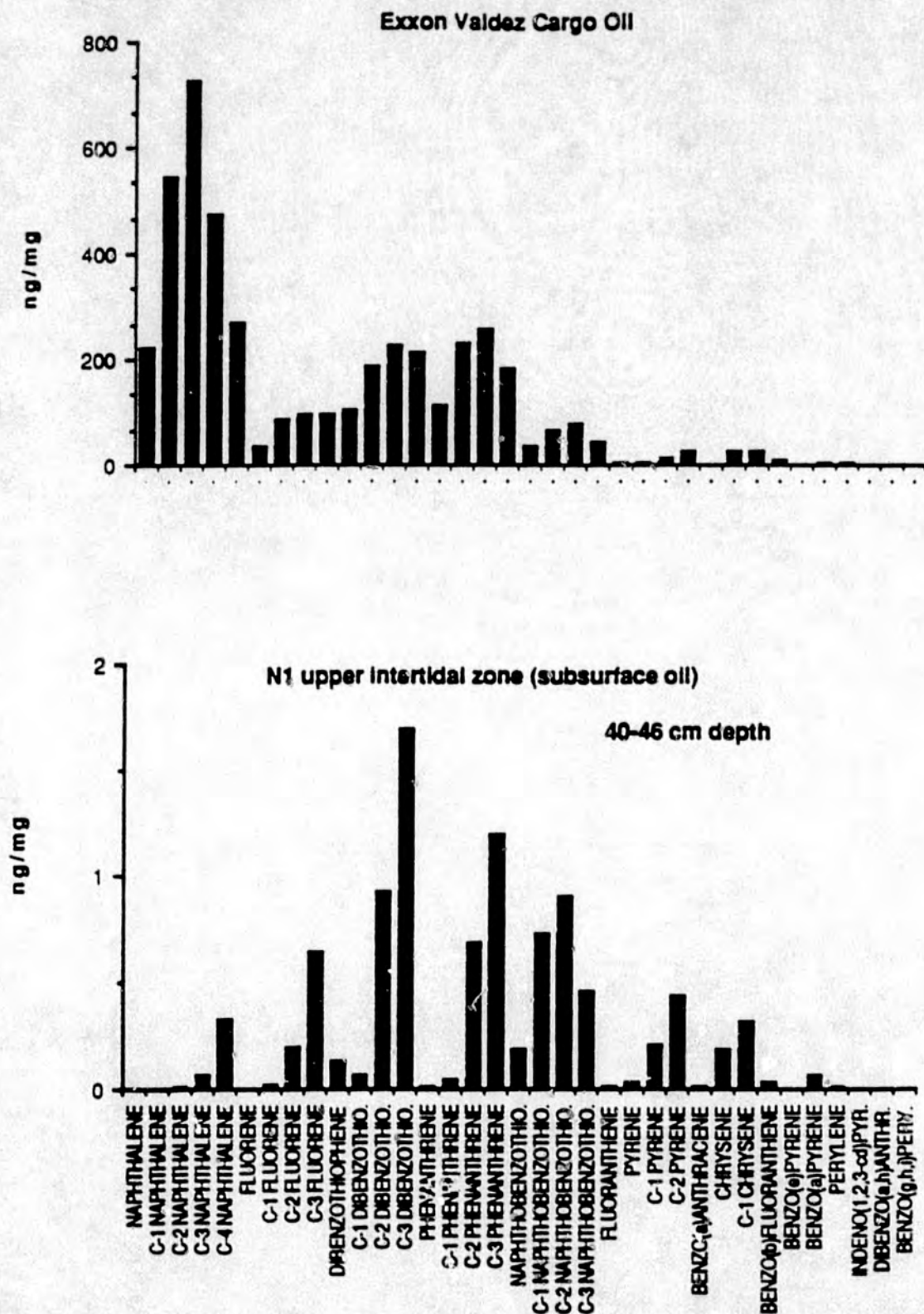


Figure I-31. Comparison of Exxon Valdez cargo oil to subsurface oil at NOAA study station N-1 upper intertidal zone (May 1990). Note the difference in scale of concentration between the plots.

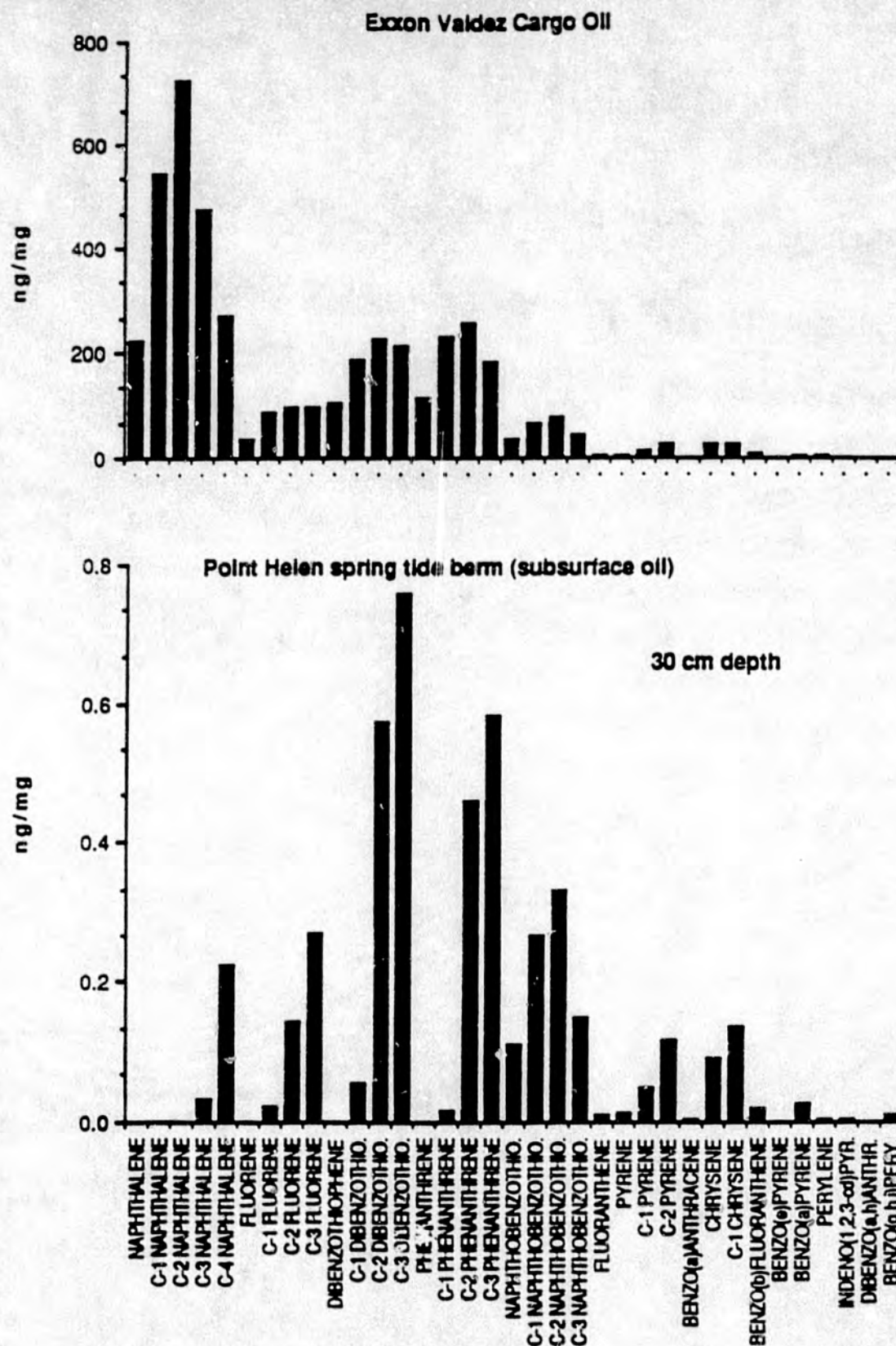


Figure I-32. Comparison of Exxon Valdez cargo oil to subsurface oil in the spring tidal berm at Point Helen (May 1990). Note the differences in scale of concentration between the two plots.

Table I-2. Concentration of Specific Compounds in Sediments at the Candidate Beaches.

GC/MS QUANT RESULTS					
STATION:	LA-19	LA-19	LA-19	LA-19	N18
SAMPLE TYPE:	mousse	tar/grav	grav./peb.	grav./peb.	grav./peb.
DEPTH:	0-5 cm	0-5 cm	0-5 cm	25-30 cm	20-25 cm
LAB ID:	N0143-2	N0143-5	N0143-6	N0143-1	N0145-10
MONTH SAMPLED:	MAY, '90	MAY, '90	MAY, '90	MAY, '90	MAY, '90
RELATED FIGURE:	F 1-24	F 1-25	F 1-26	F 1-27	F 1-28
COMPOUND	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)
NAPHTHALENE	0.1400	0.0021	ND	ND	ND
C-1 NAPHTHALENE	12.0000	0.1200	ND	ND	ND
C-2 NAPHTHALENE	84.0000	1.0000	ND	0.0014	0.0700
C-3 NAPHTHALENE	98.0000	1.6000	ND	0.0540	0.2900
C-4 NAPHTHALENE	65.0000	1.2000	0.0042	0.2400	1.7000
FLUORENE	4.5000	0.0820	ND	0.0000	0.0000
C-1 FLUORENE	20.0000	0.4800	0.0003	0.0290	0.0600
C-2 FLUORENE	30.0000	0.7400	0.0004	0.1500	0.5100
C-3 FLUORENE	28.0000	0.5000	0.0037	0.2600	0.9100
DIBENZOTHIOPHENE	26.0000	0.3900	ND	0.0007	0.3100
C-1 DIBENZOTHIOPHENE	71.0000	1.2000	0.0013	0.1100	0.1800
C-2 DIBENZOTHIOPHENE	110.0000	2.2000	0.0087	0.6700	1.7000
C-3 DIBENZOTHIOPHENE	100.0000	1.9000	0.0160	0.8100	2.5000
PHENANTHRENE	33.0000	0.4500	ND	ND	0.0400
C-1 PHENANTHRENE	88.0000	1.7000	0.0002	0.0870	0.1100
C-2 PHENANTHRENE	110.0000	1.9000	0.0073	0.5900	1.1000
C-3 PHENANTHRENE	86.0000	1.5000	0.0160	0.6800	1.7000
NAPHTHOBENZOTHIOPHENE	18.0000	0.2500	0.0036	0.1200	0.2000
C-1 NAPHTHOBENZOTHIOPHENE	39.0000	0.5900	0.0160	0.2900	0.9000
C-2 NAPHTHOBENZOTHIOPHENE	45.0000	0.7600	0.0510	0.3500	1.1000
C-3 NAPHTHOBENZOTHIOPHENE	30.0000	0.5400	0.0440	0.1600	0.5900
FLUORANTHRENE	1.4000	0.0230	0.0002	0.0078	0.0600
PYRENE	2.0000	0.0350	0.0008	0.0210	0.0400
C-1 PYRENE	6.0000	0.1000	0.0023	0.0450	0.2600
C-2 PYRENE	14.0000	0.1900	0.0160	0.1300	0.5100
BENZO(a)ANTHRACENE	0.5200	0.0057	0.0000	0.6800	0.0000
CHRYSENE	13.0000	0.2000	0.0160	0.1000	0.2300
C-1 CHRYSENE	9.3000	0.2300	0.0190	0.1800	0.4100
BENZO(b)FLUORANTHRENE	3.1000	0.0400	0.0028	0.0240	0.0400
BENZO(e)PYRENE	ND	0.0040	0.0000	0.0006	0.0100
BENZO(a)PYRENE	3.7000	0.0530	0.0073	0.0280	0.1000
PERYLENE	0.8800	0.0088	ND	0.0110	ND
INDENO(1,2,3-cd)PYR.	0.7700	0.0013	ND	0.0200	ND
DIBENZO(a,h)ANTHR.	0.5200	ND	ND	0.0160	ND
BENZO(g,h,i)PERY.	1.2000	0.0097	0.0007	0.0200	ND

All values are valid to two significant figures only.

Table I-2. Cont.

GC/MS QUANT RESULTS				
STATION:	N18	N18	N1	KN-405
SAMPLE TYPE:	grav./peb.	grav./peb.	grav.	grav./peb.
DEPTH:	30-35 cm	20-25 cm	40-46 cm	30 cm
LAB ID:	N0145-9	N0145-11	N0145-5	N0143-3
MONTH SAMPLED:	MAY, '90	MAY, '90	MAY, '90	MAY, '90
RELATED FIGURE:	F 1-29	F 1-30	F 1-31	F 1-32
COMPOUND	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)
NAPHTHALENE	ND	ND	ND	ND
C-1 NAPHTHALENE	0.0400	0.0100	ND	ND
C-2 NAPHTHALENE	2.4000	0.6200	0.0100	0.0014
C-3 NAPHTHALENE	12.0000	3.0000	0.0600	0.0325
C-4 NAPHTHALENE	16.0000	5.6000	0.3300	0.2354
FLUORENE	0.1000	0.0300	ND	ND
C-1 FLUORENE	2.2000	0.6100	0.0200	0.0223
C-2 FLUORENE	0.6100	1.9000	0.2000	0.1444
C-3 FLUORENE	9.6000	3.1000	0.6400	0.2690
DIBENZOTHIOPHENE	0.6000	0.4600	0.1300	ND
C-1 DIBENZOTHIOPHENE	5.9000	1.3000	0.0600	0.0554
C-2 DIBENZOTHIOPHENE	18.0000	5.5000	0.9200	0.5739
C-3 DIBENZOTHIOPHENE	19.0000	5.9000	1.7000	0.7578
PHENANTHRENE	0.6100	0.1600	0.0100	ND
C-1 PHENANTHRENE	5.0000	1.2000	0.0400	0.0172
C-2 PHENANTHRENE	17.0000	4.6000	0.6900	0.4598
C-3 PHENANTHRENE	18.0000	4.5000	1.2000	0.5818
NAPHTHOBENZOTHIOPHENE	2.2000	0.6100	0.1900	0.1095
C-1 NAPHTHOBENZOTHIOPHENE	7.1000	2.1200	0.7300	0.2680
C-2 NAPHTHOBENZOTHIOPHENE	7.9000	2.5400	0.9000	0.3321
C-3 NAPHTHOBENZOTHIOPHENE	5.7000	1.3700	0.4600	0.1488
FLUORANTHRENE	0.2500	0.0200	0.0100	0.0090
PYRENE	0.4100	0.1100	0.0300	0.0134
C-1 PYRENE	2.3000	0.6900	0.2100	0.0489
C-2 PYRENE	4.1000	1.3000	0.4400	0.1161
BENZO(a)ANTHRACENE	0.0600	0.0000	0.0100	0.0033
CHRYSENE	2.3000	0.5600	0.1900	0.0904
C-1 CHRYSENE	3.1000	0.9200	0.3200	0.1368
BENZO(b)FLUORANTHRENE	0.2900	0.0800	0.0300	0.0195
BENZO(e)PYRENE	ND	ND	ND	ND
BENZO(a)PYRENE	0.6700	0.2300	0.0600	0.0265
PERYLENE	0.0000	ND	0.0100	0.0034
INDENO(1,2,3-cd)PYR.	0.0000	ND	ND	0.0031
DIBENZO(a,h)ANTHR.	0.0000	ND	ND	ND
BENZO(g,h,i)PERY.	0.1000	0.0300	ND	0.0094

All values are valid to two significant figures only.

Table I-2. Cont.

GC/MS QUANT RESULTS		
STATION:	AP-10	AP-10
SAMPLE TYPE:	-	-
DEPTH:	50-60 cm	5-15 cm
LAB ID:	B8	B24
MONTH SAMPLED:	Jan. '90	Sept. '89
RELATED FIGURE:	-	-
COMPOUND		
NAPHTHALENE	0.0008	0.0000
C-1 NAPHTHALENE	0.0000	0.0000
C-2 NAPHTHALENE	0.1500	0.0071
C-3 NAPHTHALENE	0.6900	0.0520
C-4 NAPHTHALENE	1.1000	0.3500
FLUORENE	0.0036	0.0000
C-1 FLUORENE	0.1500	0.0260
C-2 FLUORENE	0.4900	0.1600
C-3 FLUORENE	0.5000	0.2800
DIBENZOTHIOPHENE	0.0100	0.0053
C-1 DIBENZOTHIOPHENE	0.2300	0.0640
C-2 DIBENZOTHIOPHENE	0.7600	0.4400
C-3 DIBENZOTHIOPHENE	0.7200	0.5310
PHENANTHRENE	0.1800	0.0070
C-1 PHENANTHRENE	0.3400	0.0980
C-2 PHENANTHRENE	0.9000	0.5200
C-3 PHENANTHRENE	0.7800	0.5800
NAPHTHOBENZOTHIOPHENE		
C-1 NAPHTHOBENZOTHIOPHENE		
C-2 NAPHTHOBENZOTHIOPHENE		
C-3 NAPHTHOBENZOTHIOPHENE		
FLUORANTHENE	0.0027	0.0000
PYRENE	0.0100	0.0110
C-1 PYRENE	0.1100	0.0810
C-2 PYRENE		
BENZO(a)ANTHRACENE	0.0000	0.0000
CHRYSENE	0.0660	0.0620
C-1 CHRYSENE	0.1400	0.1400
BENZO(b)FLUORANTHENE	0.0000	0.0075
BENZO(e)PYRENE		
BENZO(a)PYRENE		
PERYLENE		
INDENO(1,2,3-cd)PYR.		
DIBENZO(a,h)ANTHR.		
BENZO(g,h,i)PERY.	0.0049	0.0000

All values are valid to two significant figures only.
 * Values given as parts per thousand in the oil.

immobile. Microbial degradation will continue, and be a function of exposed surface area of the oil, nutrient availability, and temperature. As the degradation continues, the composition of the subsurface oil will become similar to that described for the heavily weathered surface sample (Figure I-26).

I.C.4. PORE WATER CHEMISTRY

In the intertidal zone, the space between the grains of sediment (the pore or interstitial space) may be filled with water or air. The water table in the sediments on the shore rises and falls with the tide and usually is somewhat higher than the tidal level due to capillary lift of water in small pore spaces and to inflow of surface runoff water from the adjacent land and upper shore. On the falling tide, the pore water drains from the sediments lying above the tide level. Most of this drainage is subsurface and the water emerges below the tide level. However, in some cases, particularly in sandy or silty sediments (or in areas with large tidal ranges), subsurface drainage can not keep pace with the rate of decrease in tidal height and some of the water drains out onto the surface of the beach above the tide level and flows down the beach face. During periods of snow melt or rain, runoff of freshwater from land mixes with the saline interstitial water and moves with it down through the beach substrate on the falling tide.

If the intertidal sediments contain subsurface deposits of oil, the interstitial water moving with the tides through the sediments may come in contact with the oil and carry away some of it in solution or in particulate form. The amount of oil removed with the flushing of intertidal water will depend on the relative amount of surface area available for contact between the oil and water and on the degree of weathering of the oil. If the subsurface sediments are saturated with petroleum, there will be little contact between the oil and interstitial water. The oil will be relatively immobile unless removed physically by storm action or man's activities. If the concentration of oil is lower and only a fraction of the available pore space is occupied by the oil (e.g., the sediment particles have a surface coating of oil), there will be substantial surface area for contact between oil

and interstitial water during each tidal cycle. Hydrocarbons may be leached continuously into the interstitial water as the interstitial water is replaced by tidal pumping and surface runoff until no leachable hydrocarbons remain. The weathered oil is somewhat less sticky than fresh crude oil, due to formation of stable oil/clay flocs (see Section II.A.5). Therefore, droplets may be dislodged by the flowing water and carried away with it.

The rate of transport of oil from the subsurface deposits depends on the amount of water that comes in contact with the oil each day and the tendency of the individual hydrocarbons remaining in the oil to move from the solid oil phase into the water phase. As the more soluble components of the oil are leached out by the flowing water, the remaining oil becomes more viscous and the rate of leaching of soluble components and dispersion of droplets into the water decreases. Thus, it can be expected that the rate of removal of oil from a subsurface oil deposit will decrease with time. Therefore, information about the composition and concentrations of petroleum hydrocarbons in the pore water is important in predicting the potential environmental fate and effects of weathered oil buried in the upper intertidal zone of some beaches in Prince William Sound.

A mathematical model was developed to predict the concentrations of PAHs (the most toxic fractions of the spilled oil) in pore water in contact with subsurface oil deposits. The model also predicts the rate at which PAHs will be leached from the deposits during tidal flushing of the intertidal zone. Validation of model predictions was provided by analysis of pore water samples from several shores where subsurface oil was present. A detailed description of the model and predicted leaching rates of PAHs from subsurface oil deposits is available from Exxon as a separate report.

In a two-phase, oil/water system, organic solutes such as PAHs will tend to become distributed between the water and oil phases according to their relative solubilities in the two phases. The distribution of the PAHs between the two phases can be expressed as a distribution or a partition coefficient. Octanol/water partition coefficients (K_{ow}) derived empirically or theoretically are frequently used to estimate the concentration of a sparingly soluble organic compound such as a PAH in water in equilibrium with a solid phase (sediment organic carbon, bulk petroleum, or the tissues of a marine organism). In the model, concentrations of

different PAHs in sediment pore water in equilibrium with subsurface oil deposits were calculated based on the K_{ow} of each PAH and its concentration in a typical sample of subsurface oil. The oil samples used to calculate concentrations of PAHs in pore water included relatively lightly weathered oil similar to that which originally came ashore, moderately weathered subsurface oil collected at several locations in Prince William Sound in January 1990, and more highly weathered subsurface oil from March 1990.

It was necessary to make several assumptions in the model. All of these assumptions were conservative (e.g., they predict higher concentrations of PAHs in pore water than are likely to occur). The major assumption is that equilibrium is reached between the deposit of subsurface oil and pore water flowing over and coming into momentary contact with the oil. This could be the case if the contact time between pore water and the oil deposit is long enough, on the order of several minutes (Karickhoff, 1980). However, it is unlikely that contact between pore water and oil will reach equilibrium.

Three sets of calculations were made with the model:

- ☐ Initial-concentration-case equilibrium calculations representative of oil at high concentrations at a weathering state of the oil when it first came ashore;
- ☐ Average-case calculations representative of the average oil loading and composition found during January sampling; and
- ☐ March-case calculations using actual oil loading and composition from March samples to predict water quality.

The concentrations of PAHs in the oily sediments were measured by gas chromatography/mass spectrometry. Data were acquired for 46 samples of subsurface oily sediments chosen to be representative of the samples taken in the winter beach monitoring program. Twelve additional subsurface sediment samples, as well as pore water samples taken from the same trenches as the sediment samples, from the March 1990 survey, were also analyzed. The inputs to the model for the three test cases were as follows:

- Initial-concentration case equilibrium calculations were made using PAH concentrations determined by taking the average plus the standard deviation from the three samples with the highest measured PAH concentrations. These samples are the least weathered samples of all those that were analyzed for PAHs. Therefore, they are reasonable representations of the concentrations of PAHs in the oil that came ashore.
- Average-case equilibrium calculations were made using the average PAH concentrations from seven subsurface sediment samples taken in January 1990.
- March-cases represent equilibrium calculations using PAH concentrations and TPH concentrations in individual samples collected during March, 1990. Pore water samples were also collected at the same locations and depths as the sediment samples.

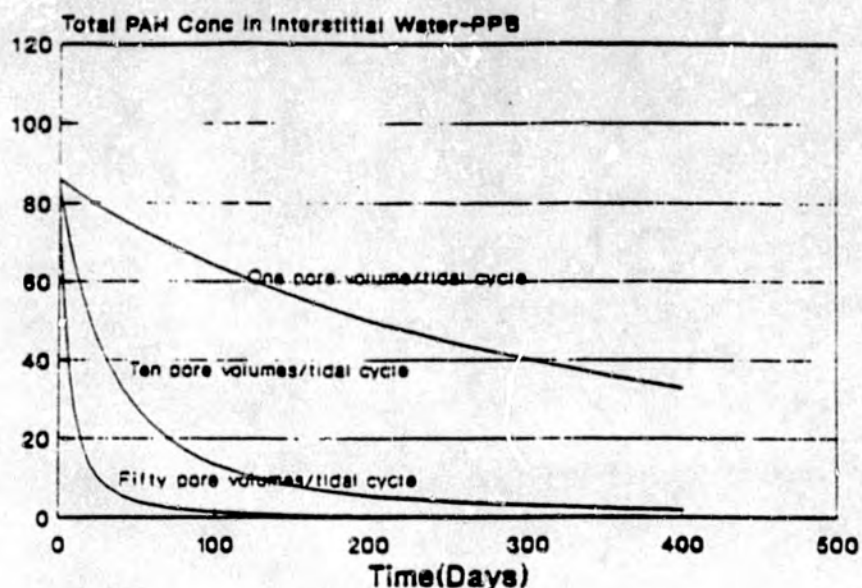
Concentrations of PAHs leaching into pore water over time were calculated based on the number of volumes of pore water that flow through the sediment during each tidal cycle. Estimates of beach flushing were made using fluid flow models that indicate that about 10 pore volumes flow through intertidal sediments of a cobble beach or a cobble beach underlain with sand during each tidal cycle. The actual flushing rate of a beach depends on several physical properties of the beach and is quite variable. Therefore, sensitivity cases were run to show the effect of flushing rates from 1 to 50 pore volumes/tidal cycle, a realistic range for different substrate types.

Initial-Concentration-Case Calculations. The leaching rates of individual PAHs were calculated over time based on the concentrations of the PAHs remaining in the subsurface oil. Values for individual PAHs were summed to produce an estimate of the leaching rate for total PAHs at three flushing rates (Figure I-33). Two tidal cycles per day were assumed for these calculations. The maximum concentration of TPH (5,000 mg/kg) was used.

In all three cases, the initial total PAH concentrations in the interstitial water were about 86 ppb. For the base case of 10 pore

Reduction in Total PAH vs Time

A) Initial Concentration Case



B) Comparison Average Case vs March Model Predictions

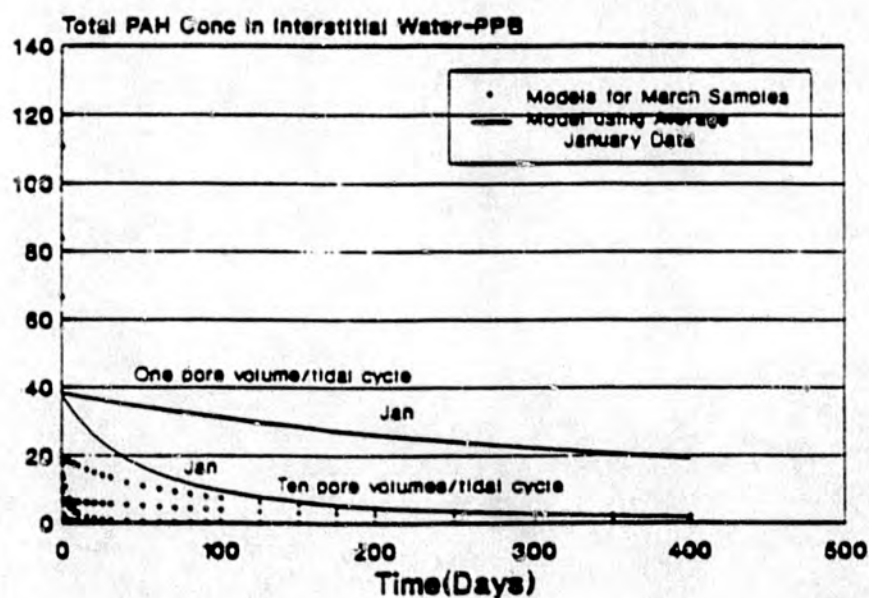


Figure I-33. Model predictions of concentrations of total PAHs in pore water in contact with intertidal deposits of subsurface oil on shores of Prince William Sound: (A) the initial concentrations case; and (B) comparison of average case and March case.

volumes/tidal cycle, the concentration drops to about 50 ppb after 20 days or 400 pore volumes of water. After 50 days, the concentration of total PAHs has dropped to about 30 ppb.

For the case of 50 pore volumes/tidal cycle, the concentration of total PAHs in pore water drops to 20 ppb within two weeks and continues to fall rapidly. On the other hand, for the case of 1 pore volume/tidal cycle, the concentration drops slowly, reaching about 65 ppb in 100 days.

Average-Case Calculation. Predicted concentrations of total PAHs for average case conditions are lower than those for the initial-case conditions (Figure I-33). The predicted initial concentration of total PAHs in pore water is about 37 ppb. The lower concentrations are due to the fact that the oil is more weathered and has lower concentrations of leachable PAHs. The rate of decrease in the concentration of total PAHs in the leach water is greater for the average case than for the initial case conditions. This is due to the lower oil loading on the subsurface sediments in January than earlier as a result of natural beach cleaning by fall and winter storms.

March-Case. The model was run using the data for the concentrations of PAHs in sediments collected in March 1990. The predicted concentrations of total PAHs in pore water are shown in Figure I-33 as dots. As expected, because of continued weathering and decreases in concentrations of oil remaining in subsurface sediments, the predicted concentrations of total PAHs in pore waters in equilibrium with the subsurface oily sediments are lower than in the January case. Predicted concentrations of total PAHs in pore water generally are below 20 ppb.

Field Observations. During the field survey in early March, pore water samples were collected at the same locations and depths as subsurface sediment samples. The results of analysis of the pore water samples for PAHs were used to validate model predictions of PAH concentrations in pore water.

The results, in general, support the premise that model predictions are conservative and that concentrations of PAHs in interstitial water in equilibrium with subsurface oil deposits are low (Table I-3). A total of eleven pairs of subsurface sediment and pore water samples were analyzed. Suspended particles or flocs were removed from the pore water samples by

Table I-3
Concentrations of Total PAHs in Pore Water and Sediments,
and of TPH in Subsurface Sediments Collected From
Several Oiled Shorelines in Prince William Sound in March 1990

Location	Site/Pit	PAH			TPH
		Sediment mg/kg	Water ng/L	Oil mg/kg	Sediment mg/kg
Foul Pass	AP-4/1	0.02	63.5	1621	12.4
Passage Pt.	AP-5/3	0.01	63.1	5347	2.25
	79.1*				
Latouche Bay	AP-12/1	0.07	709.9	836	82.7
Sleepy Bay	AP-13/1	32383	14293	5684	5697
Sleepy Bay	AP-13/4	0.14	124	3261	43.6
Sleepy Bay	AP-13/6	0.14	3821	2937	48.3
Latouche	AP-14/1	17899	10715	3271	5472
Latouche	AP-14/2	0.05	119.9	1693	32
NW Evans I.	AP-15/2	1.06	198.4	2684	394.2
NW Evans I.	AP-15/EB**		148.1		
S Elrington I.	AP-18/2	0.14	546	10543	13.2
Reference Site	AP-21C/1	0.0005	118.9	662	0.47
Blank		0.002	20.4		0.004
Prudhoe Bay Crude Oil				16556	

*Unfiltered sample

**Equipment blank

settling or filtration. Concentrations of PAHs in the water (presumably in solution or colloidal suspension) were uniformly low. Only three samples of pore water contained more than 1 ppb total PAHs in solution. Six of the eleven samples had concentrations below those measured in the equipment blank.

In May 1990, additional "pore water" samples were collected and analyzed for trace level PAHs by a compound-specific GC/MS method. The samples were collected at the sediment-water interface during falling tides and do not represent pore water by normal definition, in that they were diluted by the tidal water flushing through the coarse substrate. Replicate samples were collected at the middle and lower substrate. The results shown in Table I-4 suggest that few PAHs are being leached out of the beach with the action of normal tides. The concentration values ranged from below detection limits (approximately 0.005 ng/ml) to a maximum value of less than 0.020 ng/ml for any individual compound at either site sampled. These values are very low, and while not true pore water, reflect the level of potential exposure to organisms living in the intertidal zone.

Figure I-34 is a comparison of the concentrations of total PAHs in pore water predicted by the model and those actually measured in pore water samples collected in March. For the two samples with concentrations of TPH greater than 5,000 ppm (AP-13-1 and AP-14-1), the model predicts concentrations of total PAHs reasonably close to actual measured concentrations.

Where concentrations of TPH in the sediment are low, PAH concentrations in the oil tend to be relatively high, and the model tends to predict initial concentrations of total PAHs in the pore water higher than those actually measured. For such samples, the model predicts a very rapid drop in the concentration of PAHs in the pore water, as evidenced in Figure I-34 by the drop in predicted concentrations between day 0 and day 1.

Figure I-33 shows in the top series of dots the concentrations of total PAHs predicted by the model in pore water in equilibrium with the two sediment samples with the highest concentrations of TPH. Because the initial model predictions and observed concentrations are similar for these samples, it is reasonable to expect rates of decrease in the concentrations of

Table I-4. Concentration of Specific Compounds in Pore Water Collected at Candidate Beaches during May 1990.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	KN405	KN405	KN405	KN405	KN405
REP. #	1	2	3	1	2
TIDAL ZONE	MI	MI	MI	LI	LI
SAMPLE TYPE	WATER	WATER	WATER	WATER	WATER
DATE SAMPLED	6/6/90	6/6/90	6/6/90	6/6/90	6/6/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	ND	ND	ND	ND	0.011
C-1 NAPHTHALENE	ND	ND	ND	ND	0.006
C-2 NAPHTHALENE	0.008	0.012	0.012	ND	0.008
C-3 NAPHTHALENE	ND	0.005	0.005	ND	0.007
C-4 NAPHTHALENE	0.006	0.011	0.011	0.007	0.013
FLUORENE	ND	ND	ND	ND	ND
C-1 FLUORENE	ND	0.014	0.014	ND	0.010
C-2 FLUORENE	ND	0.006	0.006	ND	ND
C-3 FLUORENE	ND	0.008	0.008	ND	0.005
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	0.007	0.007	ND	0.005
C-2 DIBENZOTHIOPHENE	0.010	0.013	0.013	0.007	0.008
C-3 DIBENZOTHIOPHENE	0.010	0.013	0.013	0.012	0.008
PHENANTHRENE	ND	ND	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND	ND	ND
C-2 PHENANTHRENE	ND	0.006	0.006	ND	ND
C-3 PHENANTHRENE	ND	0.006	0.006	0.006	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	0.006	0.006	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	0.010	0.010	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
FLUORANTHENE	ND	ND	ND	ND	ND
PYRENE	ND	ND	ND	ND	ND
C-1 PYRENE	ND	ND	ND	ND	ND
C-2 PYRENE	ND	ND	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND	ND	ND
CHRYSENE	ND	ND	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND	ND	ND
BENZO(b)FLUORANTHENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	ND
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHR.	ND	ND	ND	ND	ND
BENZO(g,h,i)PERY.	ND	ND	ND	ND	ND

est. det. limit 0.005 ng/mL

All values are valid to 2 significant figures only.

Table I-4. Cont.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	KN405	LA18	LA18	LA18	LA18
REP. #	3	1	2	3	1
TIDAL ZONE	LI	MI	MI	MI	LI
SAMPLE TYPE	WATER	WATER	WATER	WATER	WATER
DATE SAMPLED	6/6/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	0.013	0.011	0.005	ND	ND
C-1 NAPHTHALENE	0.007	0.007	ND	ND	ND
C-2 NAPHTHALENE	0.007	0.007	ND	ND	ND
C-3 NAPHTHALENE	ND	0.006	ND	ND	ND
C-4 NAPHTHALENE	0.011	ND	ND	0.006	0.006
FLUORENE	ND	ND	ND	ND	ND
C-1 FLUORENE	ND	ND	ND	ND	ND
C-2 FLUORENE	ND	ND	ND	ND	ND
C-3 FLUORENE	ND	ND	ND	ND	ND
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-2 DIBENZOTHIOPHENE	0.006	ND	ND	ND	ND
C-3 DIBENZOTHIOPHENE	0.008	ND	ND	ND	ND
PHENANTHRENE	ND	ND	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND	ND	ND
C-2 PHENANTHRENE	ND	ND	ND	ND	ND
C-3 PHENANTHRENE	ND	ND	ND	ND	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
FLUORANTHRENE	ND	ND	ND	ND	ND
PYRENE	ND	ND	ND	ND	ND
C-1 PYRENE	ND	ND	ND	ND	ND
C-2 PYRENE	ND	ND	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND	ND	ND
CHRYSENE	ND	ND	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND	ND	ND
BENZO(b)FLUORANTHRENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	ND
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYRENE	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHRACENE	0.006	ND	ND	ND	ND
BENZO(g,h,i)PERYLENE	ND	ND	ND	ND	ND

est. det. limit 0.005 ng/mL

Table I-4. Cont.

GC/MS QUANT RESULTS			
SAMPLE LOCATION	LA18	LA18	EQ. BLANK
REP. #	2	3	NA
TIDAL ZONE	LI	LI	NA
SAMPLE TYPE	WATER	WATER	WATER
DATE SAMPLED	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	ND	0.005	ND
C-1 NAPHTHALENE	ND	ND	ND
C-2 NAPHTHALENE	ND	ND	ND
C-3 NAPHTHALENE	ND	ND	ND
C-4 NAPHTHALENE	ND	0.005	ND
FLUORENE	ND	ND	ND
C-1 FLUORENE	ND	ND	0.006
C-2 FLUORENE	ND	ND	ND
C-3 FLUORENE	ND	ND	ND
DIBENZOTHIOPHENE	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND
C-2 DIBENZOTHIOPHENE	ND	ND	ND
C-3 DIBENZOTHIOPHENE	ND	ND	ND
PHENANTHRENE	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND
C-2 PHENANTHRENE	ND	ND	ND
C-3 PHENANTHRENE	ND	ND	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
FLUORANTHENE	ND	ND	ND
PYRENE	ND	ND	ND
C-1 PYRENE	ND	ND	ND
C-2 PYRENE	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND
CHRYSENE	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND
BENZO(b)FLUORANTHENE	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND
PERYLENE	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	ND	ND
DIBENZO(a,h)ANTHR.	ND	ND	ND
BENZO(g,h,i)PERY.	ND	ND	ND
est. det. limit 0.005 ng/mL			

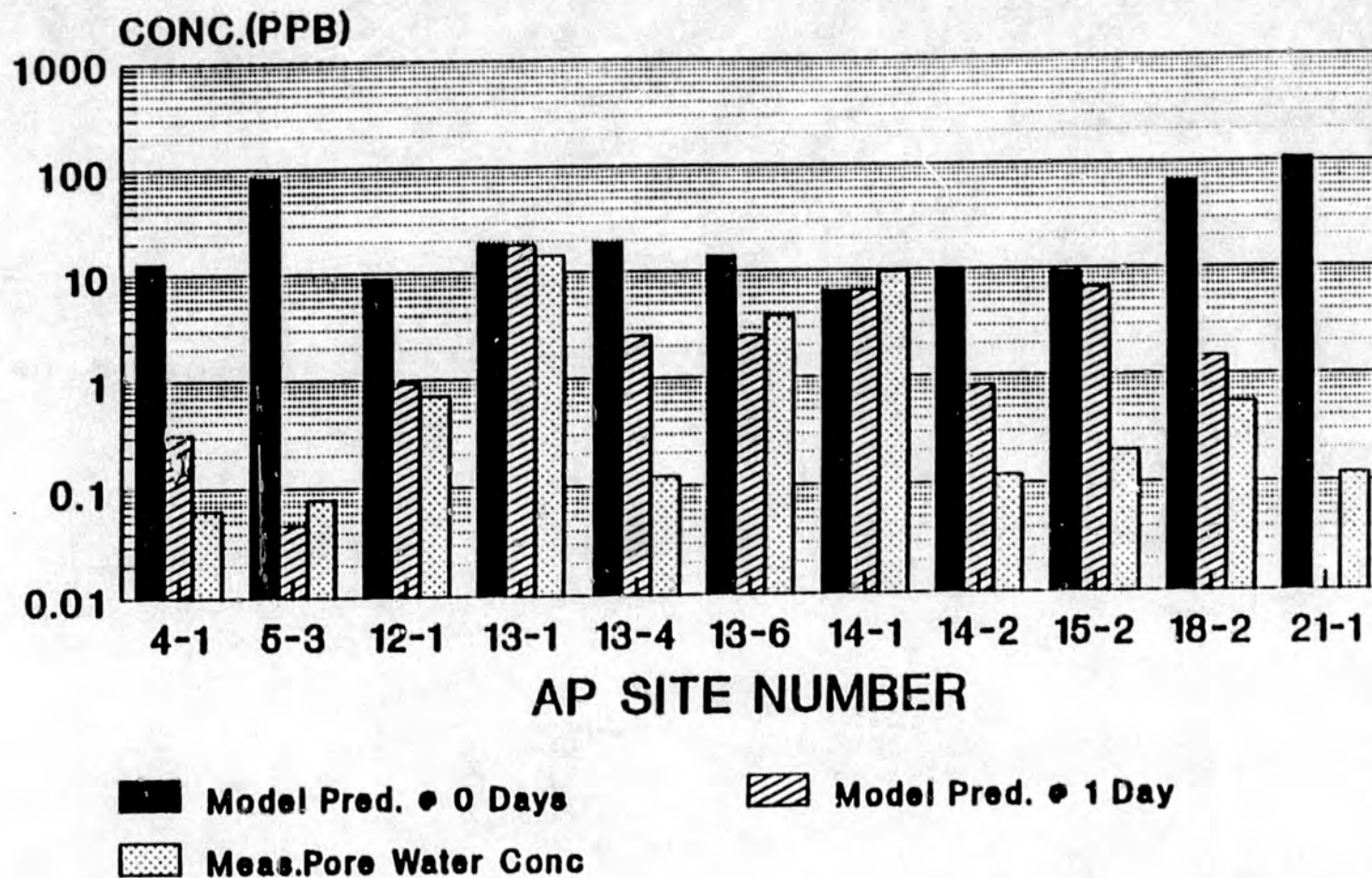


Figure I-34. Comparison of concentrations of total PAHs in pore water of sediments collected from oiled shores in Prince William Sound in March, 1990, predicted by the model and actually measured in pore water samples.

PAHs in pore water similar to these projections. The use of 10 pore volumes/tidal cycle in the model seems to predict changes over time in the concentrations of PAHs in pore water quite well. In the model, PAH concentrations in pore water approach zero in about 200 days. However, if the amount of flushing of the shore is significantly different from 10 pore volumes/tidal cycle, the predicted rate of decrease in the concentration of PAHs in pore water with time would change accordingly.

The concentrations of total PAHs in pore water samples in direct contact with oily subsurface sediments, predicted or measured, are below the concentrations of total PAHs of petroleum origin known to be acutely toxic to marine organisms. In addition, these initial concentrations will be diluted substantially as the sediment interstitial water containing PAHs mixes with clean interstitial water and as the mixed interstitial water drains from the beach and mixes with the shallow subtidal water. This dilution, which is likely to be substantial, will render the pore water completely nontoxic to marine organisms on the lower shore and in nearshore subtidal waters.

I.C.5. BEACH HYDRAULICS

Point Helen

Tidal Flushing. The sedimentology of the beach surface on this section is characterized by a coarse (pebble-cobble-boulder) and porous layer that is one or two particles thick. Water movement through this layer is unrestricted. Groundwater flow emerges through this layer in the lowest parts of the intertidal zone.

The subsurface is characterized by mixed sediments, with fine material (sands and granules) present in the interstices between the coarse material. Water movement and flow rates are restricted by the small size of the pore spaces.

The net effects of this two-flow system are that:

- a) the surface armor layer is continuously washed by water (waves) during periods of tidal inundation and dries out when exposed,
- b) the subsurface sediments generally remain wet,

- c) in the zone of wave action, which is dictated by the tidal water level, uprush is followed immediately by infiltration, and
- d) backflow following uprush, under the influence of gravity, occurs beneath the surface of the beach primarily at the interface of the surface coarse layer and the subsurface mixed sediments.

This section is therefore characterized as having an active surface zone, in which flushing takes place on a regular basis with each phase of the tidal cycle, and a less active subsurface zone with lower flushing rates.

Freshwater Runoff. No streams cross the section. There will be runoff from the backshore across and through the intertidal zone during periods of rainfall and snow melt.

Sleepy Bay

Tidal Flushing. These coarse (pebble-cobble-boulder) sediments have few fines, so that the interstitial spaces are open and water flow is unrestricted.

Freshwater Runoff. There is year-round, non-channelized freshwater runoff in the west section of the unit and there is a year-round anadromous stream within this section. There will be runoff from the backshore across and through the intertidal zone during periods of rainfall and snow melt.

I.C.6. TREATMENT HISTORIES

Point Helen (KN-405; AP-10; N-1)

This segment was surveyed by a SCAT team on 26 June 1989. The U.S. Coast Guard reported treatment began on 6 July.

Treatment:

- a) Deluge header hose flood.
- b) Cold water, high pressure wash.
- c) Warm/hot water, moderate pressure wash.
- d) Hot/steam water, high pressure wash.

- e) MAXI Barge.
- f) OMNI Boom.
- g) Bioremediation.

Sleepy Bay (LA-18; AP-13C; N-18)

This segment was surveyed by a SCAT team on 17 June 1989. The U.S. Coast Guard reported treatment began on 22 June.

Treatment:

- a) Deluge header hose flood.
- b) Cold water, high pressure wash.
- c) Warm/hot water, moderate pressure wash.
- d) Back hoe tractor was used to move oiled sediments adjacent to the anadromous stream where they were scheduled to be washed and then returned to the stream bank. When the stream was diverted, it drained subsurface, at its seaward end. Salmon spawning season was nearing and ADF&G stopped tractor activity. Clean material from the lower portion of the intertidal zone was used to reline the stream banks.
- e) Manual labor crews worked on shoreline with shovels, rakes, and chainsaws.

I.C.7. BIOLOGICAL CONDITIONS

Sources of Data and Information

There are no quantitative baseline data with which to describe the intertidal biological communities that inhabited the candidate beaches before the spill. Without these data it is difficult to estimate the characteristics of the intertidal communities that would likely reinhabit the beaches following recovery from the spill. There are data available from other sites within Prince William Sound that were surveyed before the spill (Rosenthal et al., 1982; O'Clair and Zimmerman, 1987; Feder and Bryson-Schwafel, 1988; Juday and Foster, 1990). They were used qualitatively and

descriptively to provide a general portrait of the types of organisms that would be expected at these beaches.

These general data were augmented with information assembled from surveys and observations made after the spill at the candidate beaches by members of the NEBA team. Observations of the presence of oil, the geomorphology of the beaches, and presence of selected biota at the candidate sites were made in the Spring Survey Assessment Team (SSAT) surveys (4 April 1990). Members of the NEBA team visited the Sleepy Bay segments in May, early June, and late June. They visited the Point Helen segment in May. During these surveys, observations were made and recordings taken on the density of plants and animals and their vertical location on the beach.

In Sleepy Bay there were some differences between the descriptions of the biota observed in May and those observed in June by the NEBA team members. These differences are discussed below in the segment descriptions. Causes of these discrepancies are speculative: They may reflect biological changes that occurred over a period of over one month, they may reflect differences in surveying methods of the team members, or they may reflect the heterogeneity of the segments.

General Description

The candidate beaches generally consist of mixed pebbles, cobbles, and boulders, with minor components of granules and sand. The larger cobbles and boulders are sufficiently stable and large to support epibenthic species and the smaller materials surrounding and underneath the cobbles and boulders support motile and infaunal species. The occurrence and abundance of intertidal species is patchy within any single beach. The patchiness is a result of many controlling factors, including the distribution of stable cobbles and boulders, exposure to breaking waves, tidal height (vertical position on the beach), proximity to freshwater, sunlight/shading, desiccation, predation, and the composition and stability of the beach materials.

The combined effects of these factors vary from beach to beach and within any single beach. The result is that the composition of intertidal

communities can differ a great deal among beaches and within the length of any beach.

Rosenthal et al. (1982) listed the most frequently occurring species for semi-protected, intertidal, mixed coarse sediments in Prince William Sound as *Monostroma* / *Ulva*, *Fucus distichus*, *Balanus* spp., unidentified acmaeids (limpets), and *Pycnopodia helianthoides* (sea star). Also relatively common were *Zostera marina* (eelgrass), *Desmarestia aculeata* (alga), *Echiurus echiurus* (echiurid worm), *Hemigrapsus oregonensis* (shore crab), *Pagurus hirsutiusculus* (hermit crab), *Littorina sitkana* (snail), *Mytilus edulis* (mussel), *Protothaca staminea* (clam), *Saxidomus giganteus* (clam), and *Evasteria troschelii* (sea star). Most of these species were observed on the post-spill surveys of the candidate beaches; the echiurid worms, clams, shore crabs, and sea stars generally were missing or relatively rare.

In 1986, Juday and Foster (1990) observed 96 animal species and 39 plant species in intertidal rocky areas of Green Island in lower Prince William Sound. After the spill, 37 of the animal species and six of the plant species were not observed. Fourteen animal species and two plant species were found in 1989 that had not been seen in 1986. Among the more common species observed at Green Island were *Balanus* spp., *Mytilus* spp., *Fucus* spp., littorine snails, and *Leathesia* spp. in the upper to mid-tidal zones. The authors attributed some of the apparent differences in the species that were present before and after the spill to differences in their sampling efforts and taxonomic skills.

Rosenthal et al. (1982) described the very distinct zonation of intertidal organisms in mixed coarse habitats of Prince William Sound. Species richness and total abundance of organisms increased from the high intertidal to lower intertidal zones. The species that were dominant also changed between vertical zones. In surveys performed in May 1990 for this NEBA, zonation was very distinct at Point Helen and less so in the Sleepy Bay segments.

Rosenthal et al. (1982) concluded, after examining many sites in Prince William Sound, "that the predictability of species composition is rather low" within distinct habitat types. Also, O'Clair and Zimmerman

(1987) reported relatively low similarity in species composition among 28 rocky substrate sites around the perimeter of the Gulf of Alaska. Therefore, interpolation of data from other sites with the same habitat type to the candidate beaches may have a low degree of accuracy. Many subtle differences in controlling environmental factors can have marked effects upon the species composition among areas.

As will be described below, the species observed in different visits after the spill at the candidate sites generally did not differ remarkably from those recorded by Juday and Foster (1990) and Rosenthal et al. (1982) at other sites before the spill. Despite the observations of relatively low predictability of species composition from site to site, there appears to be a rather predictable "core group" of intertidal species at most locations. This assemblage of species generally consists of one to several species of barnacles, the mussel *Mytilus edulis*, littorine snails, limpets, *Fucus*, and several species of other brown and green algae attached to rocks. Several species of polychaetes, clams, gammarid amphipods, hermit crabs, and sea stars comprise the core group of species common among or under the coarse clasts. The abundance of these organisms differs among the vertical zones of the beaches.

LA-17. Sleepy Bay, Latouche Island

Segment LA-17 is located to the east of the candidate site, LA-18. The substrate consists of a very heterogeneous mixture of large, angular boulders; angular, flattened boulders; cobbles; gravel; and small amounts of coarse sand and shell fragments. At the southeast end of the segment, there are rock outcrops that were not surveyed for this report. The following descriptions were based upon surveys performed in May, early June, and late June of the portions of the beach segments that consisted mainly of unconsolidated materials.

The lower tide zone included cobble which, in May, was covered with a heterogeneous algal assemblage, sparse to thick in places. *Ulva*, *Enteromorpha*, *Fucus*, and filamentous brown and green algae were dominant. By late June, the abundance of opportunistic green algae was low. Small *Fucus* and other brown algae were abundant in the lower

intertidal zone wherever large rocks occurred. Patchy groups of large barnacles, many dead serpulid worms, and mussels occurred in this zone. Detached and empty mussel shells were present in May in numbers equivalent to those that were alive, but dead mussels were not observed in June. One dead *Mytilus* adult was observed in May that still had the internal soft parts intact, indicating that it had died recently. Limpets occurred in densities of up to about 20 m² and, in May, about 50% of the shells were dead and empty. This rate of mortality was not observed in June. Littorine snails were not observed in May, but were common in June, both on the surface of rocks and underneath rocks (often with egg masses). In late June, the abundance of these snails was still high, but the abundance of the egg masses had decreased. Young-of-the-year barnacles, mussels and limpets were common in May and/or June on stable rocks, sometimes in dense patches. Animals living among and under the boulders in May were: isopods (probably *Idotea*, 2-5/m² and probably *Isosphaeroma*, 20/m²), hermit crabs (abundant, 10/m²), mussels, and a few gunnels. In June the common animals included limpets (several species), amphipods (*Gammarus oregonensis* and others), isopods (*Idotea wosnesenskii* and others), nereid and other polychaetes, hermit crabs, and spawning gunnels. The egg masses of gunnels were not found in late May. As many as seven species of sea star and the snail *Nucella lamellosa* were observed in June, but none of these species was seen in May.

As observed in other segments and as reported by Rosenthal et al. (1982), species diversity and organism density decreased upslope in the intertidal zone. However, on steeper portions of the segment, the density and diversity of biota seemed to have been maintained higher up the shore than elsewhere, probably due to the steeper gradient and more shaded and sheltered aspect of the beach.

Much of the mid-tidal zone consisted of very large, angular black cobbles and boulders overlying pebbles, and granules/sand. Attached to the boulders was a more sparse assemblage of the algae found in the lower tide zone. In May *Littorina* occurred in patches of approximately 20-50/m², and about 10% of the shells were dead and empty. Young-of-the-year *Fucus* and both young and old barnacles and mussels populated this segment of beach, sometimes in dense patches. Large terebellid worms, small gammarids

(10/m²), and hermit crabs (5-10/m²) were found among pebbles under boulders. Limpets, gunnels, and a polychaete worm (*Nereis* or *Nephtys*) were rare in May and abundant in June. A very large rock outcrop located within the segment had a relatively dense assemblage of *Fucus*, barnacles, and mussels growing on it, some of which were small, young individuals.

Much of the upper zone consisted of large boulders, oiled cobbles and pebbles, and an underlying hash made of shells and coarse sand. About 10-50% of the barnacles in the upper zone were dead in May. Most of the larger rocks had a cover of diatom scum and, occasionally, some *Fucus*. Young *Fucus* plants were observed in June. Patches of mussels and *Littorina* (20/m²) were located in this region. Oligochaetes (probably an Enchytraeid) were common in the sand in May (abundances of up to 50/m²), but were less common in June. In June, barnacles (both recent recruits and adults), *Mytilus*, *Littorina*, amphipods, limpets, and *Pagurus* were encountered, well above the vertical height in which they are usually found on other shores.

Overall, this segment has a moderately dense community of plants and animals. The species found in the segment generally are similar to those found elsewhere in Prince William Sound. Reflecting the heterogeneous geomorphology of the segment, the biota are very patchy in distribution, as is typical of the beaches of Prince William Sound. The main consistent trend was the increase in species density and diversity downslope. The upper tidal zone that remains most heavily oiled is mostly depauperate of biota, but the depauperate condition of the upper tidal zone is typical of that observed in unoiled shores throughout Prince William Sound (Rosenthal et al., 1982). The transition in biological community composition among the low-, mid-, and upper tidal zones is gradual, whereas at Point Helen, the transition between the lower and mid-tidal zones is very abrupt. Some species were noticeable in their absence in May, including predatory sea stars (*Pycnopodia helianthoides*) and whelks (*Thais*, ne *Nucella*). However, they were observed in June. An unusual population of oligochaetes (probably an Enchytraeid) has invaded the upper tidal zone sediments, presumably consuming the bacteria that are degrading the oil.

LA-18. Sleepy Bay, Latouche Island

The 4 April 1990 SSAT inventory for Site LA-18 included moderate to sparse abundances of barnacles in the mid-tide zone, mussels were dense to moderate to sparse, gastropods from dense to moderate to sparse to rare, and *Fucus* classified as dense to moderate to sparse in the mid-tide zone. Filamentous green algae were in the mid and low tide zones, and amphipods were dense under the cobble with two kinds of gastropods. Low occurrence of mortality in mussels was reported by SSAT on 4 April 1990. The biota in this segment were very patchy, reflecting the heterogeneous distribution of stable substrates.

The morphology of this segment has changed since the spill because of the meandering of an anadromous stream that bisects the segment. The lower part of the stream, including a small delta, has moved considerably since the site was first surveyed last year.

As observed in May and June of 1990, the substrate is very heterogeneous, grading from predominantly small cobbles on the stream banks to large boulders and rock outcrops in the western part of the segment. There is a small sand/silt beach at the low tide line in the easternmost part of the segment where it borders with segment LA-17. Generally, there was very little fine-grained sand and gravel in the middle and upper tidal zone. However, in some locations, fine-grained sediments were abundant below the surface cobbles. Much of the fine sediments were plate-like, probably derived from natural pulverization of the shale that was an abundant component of the cobbles and boulders on the beach surface.

The biota observed in LA-18 in May 1990 consisted mainly of the same organisms observed in LA-17. The biota were most sparse in the upper tidal zone, and rapidly increased in diversity and density downslope. Organisms that usually occurred in patches in the middle tidal zone often occurred in continuous dense populations in the lower tidal heights. An eelgrass bed occurs in the subtidal zone. The incidence of dead animals observed in LA-18 in May was somewhat lower than that observed in LA-17. One moribund *Protothaca* clam was observed in May upon the beach surface. Many dead, necrotic fronds of detached *Fucus* were found among the rocks.

In May there were many species of brown and green algae, limpets, barnacles, mussels, and serpulid worms on the rocks with isopods, hermit crabs, mussels, and a few clams and gunnels under the rocks in both the mid- and lower tidal zones. The mid-tidal zone community consisted mainly of green and brown algae (including *Ulva* and *Fucus*), *Littorina* spp., barnacles, mussels, and a few limpets on the rocks and isopods; gammarid amphipods; and terebellid worms and gunnels under the rocks. Their abundance generally increased downslope. Egg masses and adults of *Littorina* were evident in May and very abundant in June. The density of egg masses decreased late in June. Less common taxa included some bryozoans, polychaetes, and hermit crabs.

No *Nucella* or sea stars were observed in May in association with small rocks, cobbles, and gravel in the eastern portion of the segment that was surveyed. One sea star was observed in early June. In late June, sea stars (particularly *Pisaster ochraceus*) were fairly abundant upon or near large boulders and rock outcrops in the western part of LA-18. In addition, a few *Pycnopodia* were observed under overhanging rock outcrops in the lower intertidal zone. *Nucella* were observed also in June, again mainly in association with large rock outcrops in the eastern portion of the segment.

Generally, the plants and animals observed in June were similar to those seen in May in all vertical zones. A few small amphipods were observed under rocks and some barnacle settlement was evident on the larger more stable boulders. In locations where oil was present in patches on the surface, no biota, except oligochaetes, were present under or among the surface cobbles. However, large rocks that had patches of tar also supported mixed age groups of barnacles. Many of the barnacles covered by the tar were dead, but an almost equal number were alive. Other animals observed in June in the middle and lower tidal zones included hermit crabs, amphipods, limpets, isopods, gunnels (some with eggs in early, but not late June), *Nereis*, at least one other species of polychaete, and bryozoans. Large Nereid worms and a few other taxa of polychaetes were encountered frequently under rocks in the lower shore where the underlying substrate was fine-grained. Very small amphipods, limpets, and littorine snails were more abundant on and under rocks in the middle and lower intertidal zones in late June than in early June.

In June serpulid worms (*Spirorbis* sp.) were dense, and mussels were patchy and sparse on and among the rocks and dense in crevices of large rock outcrops. About 1% of the mussels were dead and the shells were empty. *Ulva* and filamentous green algae were present on stable rocks.

Many of the brown algae on the lower shore and in the shallow subtidal zones were smaller than usual and the distal parts of the fronds of many of the plants were bleached white. However, these damaged plants were accompanied by abundant young plants and newly recruited littorine snails, amphipods, mussels, and barnacles.

In May the pebbles and small cobbles in the middle and upper zones near the mouth of the creek were relatively depauperate. They generally were inhabited by only a thin film of a filamentous green alga (probably *Monostroma*) and some *Littorina*.

The biota were sparse in the upper tidal zone, consisting mainly of diatoms, a few mussels, barnacles, and *Littorina* on the cobble surfaces and relatively abundant oligochaetes and a few amphipods under the cobbles. The depauperate nature of the upper intertidal zone is typical of that encountered throughout Prince William Sound

Overall, the biological community of this segment was very patchy, differing considerably in both density and diversity along the segment and across vertical horizons within the segment. The upper tidal zones were more depauperate than the lower zones. Parts of the lower tidal zone were relatively densely populated by a number of marine plants and animals. Some species, including predator sea stars and snails, were either absent or present in very low density among unconsolidated materials in May, but they were sparse to common in abundance near or on large rock outcrops in June. A relatively dense population of oligochaetes had invaded the upper tidal zone sediments, presumably consuming the bacteria that are degrading the oil.

Sleepy Bay: A Summary

Without the benefit of pre-spill, baseline information, it is difficult to estimate accurately the degree to which the biota of Sleepy Bay have

recovered from the effects of the spill and subsequent cleanup efforts. The composition of the "normal," pre-spill intertidal community is unknown.

The intertidal biota of Sleepy Bay, however, are not dramatically different than the communities previously described for similar habitats elsewhere in Prince William Sound. The group of species that would be expected to be dominant generally were present, often abundant, in Sleepy Bay. The numbers of species found generally approximated the numbers of species observed elsewhere in the Sound. The patchiness and heterogeneity both along and across the beaches were as described for other beaches. The differences in biota observed in May and June are not unusual: They could be attributable to the natural variability in the communities over time and space, to differences in the survey methods of the investigators, to differences in the habitat types that were surveyed, or they could reflect stages in the recovery of the biota in the beaches.

Mortalities among mussels, barnacles, limpets, snails and macroalgae that were observed in May could be attributable to a number of factors. A battery of natural factors, such as cold winter weather, freshwater runoff in the spring, disease, predation, and old age, could account for some percentage of the mortalities. The oil and subsequent cleanup efforts probably contributed to some of the mortalities along with these natural factors. The relatively persistent hard shells of animals such as mussels, limpets, and barnacles would remain for many months or years following the death of the organisms. A few bivalves that were either moribund or dead and still contained their internal soft parts in May suggest that some animals were dying in the spring, but the cause of these deaths is unknown and the number of animals observed dying was extremely small. Some adult mussels that survived the spill had deformities in shell produced some time ago along the posterior fringes of their shells, but more recent accretions of shell material appeared normal.

The majority of the Sleepy Bay beaches were inhabited by intertidal organisms in May and June. Only a very few isolated areas in the upper tidal zone where surface oil remained in high concentrations were still azoic. In some areas where surface oil under large rocks was relatively highly concentrated, very few infaunal organisms existed or only the

infaunal oligochaetes were present. The presence of abundant populations of the oligochaetes is unusual and probably a result of the spill.

The presence of large adult invertebrates in the spring indicates that many animals, particularly those attached to large rocks and those in the lower tidal zone, survived the effects of the spill and cleanup. Large adult barnacles and mussels were often attached to large rocks.

In addition, there is considerable evidence that the biota of the Sleepy Bay beaches are recovering. The recolonization of the beaches by all of the major macroscopic taxa is in progress as evidenced by the presence of young individuals and/or egg masses of some species. It appeared that barnacles recolonized some of the rocks as early as last fall and very young barnacles were common in most areas in May and June. Young-of-the-year mussels, littorine snails, limpets, *Fucus*, and other plants were common in most areas. Young littorine snails were abundant late in June in areas where they were absent or sparse in May. Highly mobile predatory snails and sea stars were migrating across the beaches from lower zones, along the beaches from adjacent areas or from the large rocks that were not heavily impacted.

The presence in the middle and lower tidal zones of several species of invertebrates (amphipods, isopods, young molluscs) generally considered to be sensitive to the effects of oil suggests that the residual subsurface oil in these zones is not having a marked effect upon these organisms. The biological communities in the lower shore are relatively dense and diverse and include many of these sensitive species.

However, in the upper tidal zone that was likely most depauperate before the spill and was most heavily impacted by the spill, some signs of the effects of residual oil remain. Amphipods generally were missing or rare in patches that remained oiled. Only oligochaetes occurred abundantly in some oiled patches and, in a few very highly oiled patches, there were no living organisms evident. Whether these effects are attributable to only the surface oil or to both surface oil and subsurface oil residues is unknown.

Overall, the intertidal biological community of Sleepy Bay is relatively healthy and clearly showing signs of recovery. Many of the species that

would be expected to inhabit the area are present. All of the major trophic levels are represented. The expected time required for full biological recovery is estimated in Section II.A.2.

KN-405. Point Helen. Knight Island

The substrate along this segment is much more homogeneous than that encountered in Sleepy Bay. Large rounded cobbles and boulders are very common and occur consistently along the segment. The biota of this segment are also much more homogeneous than those observed in Sleepy Bay. The most striking feature of the intertidal community in this segment is the *Alaria* assemblage in the lower tidal zone.

The lower tide zone consisted of large, weathered, rounded boulders and cobble overlying gravel and pebbles. The intertidal community in this zone is dominated by a very dense, complex algal mat, consisting mainly of the brown alga *Alaria marginata* (at the -2.0-foot tide level). *Porphyra*, *Enteromorpha*, and *Ulva* also occur in this mat, but were much less abundant than *Alaria*. Barnacles and mussels were present, but not abundant (S. Stoker, April 1990). Some species other than *Alaria marginata* gradually diminished in abundance up to mid-tidal levels, forming a thin carpet along with colonial diatoms. The transition between the cobbles and boulders with *Alaria* and those without *Alaria* is very distinct. Under the *Alaria* and boulders, gammarid amphipods, caprellid amphipods, cheilostome bryozoan colonies, and hermit crabs were abundant. Rare in numbers were oligochaetes, polychaetes, and the bryozoan *Bugula* sp. Many sea stars (*Pycnopodia heliosthoides*), but no whelks (*Nucella*) were observed. Offshore, some harbor seals, a sea otter, and a bald eagle were observed.

The mid-tide zone was made up of large, round boulders with very little epifauna. Limpets, *Littorina*, *Enteromorpha*, and diatoms made up the sparse coverage. Under rocks, the gravel and sand matrix supported a few gammarids, gunnels, cheilostome bryozoans, and *Pycnopodia*. Egg masses from *Littorina* were apparent.

The sediments of the upper tide zone grade from small cobble/boulders to a gravelly storm berm. The beach materials are smaller

material than they are in the mid-tidal zone (see Section I.C.2). There is a gradual transition between the biota of the mid-tidal zone and that of the upper zone on this beach. Oligochaetes and a few nemerteans within the coarse sand and pebbles are the only animals found in upper part of this zone. On the large monolithic rock within the segment, there was a sparse population of barnacles.

In summary, Point Helen is an exposed beach consisting of an armor of cobble and boulders, with an underlying layer of finer material. Sand is less common here than at Sleepy Bay. The beach is relatively broad, and there is a distinct *Alaria*/algae assemblage starting abruptly at approximately the -2.0-foot tide level. The upper intertidal zone does not have observable epifauna, and the infauna consists largely of oligochaetes and some nemerteans. *Littorina* snails are numerous lower on the beach in the mid-tidal zone, and were reproducing in May 1990. Many egg masses were located on the undersurfaces of large cobbles or boulders. In the mid- and lower zones, new barnacle spat were numerous, and a film of green algae covered the tops of some of the larger rocks and boulders. No hermit crabs, *Nucella*, or sea stars were present in the middle and upper tidal zones. The sea stars normally would not be expected in the middle and upper zones in order to avoid desiccation at low tides. Hermit crabs and sea stars frequently occurred in the lower tidal zone among the dense algae.

Because of the lack of pre-spill baseline information, it is not possible to estimate the degree of progress being made in the recolonization of this beach segment. The very dense populations of plants in the lower tidal zone would suggest that this community was not affected by the spill. In contrast, the middle and upper zones remain very depauperate. It is unknown if this depauperate condition of the middle tidal zone is "normal."

I.C.8. HUMAN USES

The human use data for the segments analyzed for rock washing is based on information collected through public meetings specifically conducted to gather public uses, public use surveys, and input from public interest groups, residents, and user groups interested in Prince William

Sound. Site specific "head counts" of the number of subsistence use, recreation, and tourism visits are not available. The following descriptions of specific human uses for the study segments are a compilation on information from the Alaska Department of Natural Resources, Prince William Sound Area Plan, "Recreation and Tourism Element," "Fish and Wildlife Element" and "Cultural Resources Element" documents dated June 1987. Referenced also is the Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" dated April 1990. Other information on cultural and subsistence uses within the specific segments was submitted by the village of Chenega (Gail Evanoff).

KN-405. Point Helen. Knight Island

Recreational uses of this segment are kayaking, camping, charter operators, scenic coastline, excellent fishing, hunting, and wildlife viewing. The Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" ranks this segment as high use. This area is also used as a concentrated purse seine/gill net area. Subsistence activities include hunting, fish drying and smoking, and seal hunting. The residents of Chenega Village have strong historic cultural ties to the area of Point Helen.

LA-18, 19. Sleepy Bay. Latouche Island

Recreational uses of the segments are camping, and moderate hunting and sportfishing. The Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" ranks this segment as moderate use. Historically, the people of Chenega have subsisted heavily off the beaches of Sleepy Bay. Gathering of gumboots, kelp, mussels, eggs, sea cucumbers, shellfish, and hunting of seal and birds were main subsistence activities as well as camping to dry and smoke fish.

II. ENVIRONMENTAL CONSIDERATIONS

II.A. BASE CASE: APPROVED 1990 TREATMENTS AND NATURAL CLEANSING

II.A.1 TRENDS IN OIL RESIDUE CONTENT OF SUBSURFACE SEDIMENT SAMPLES FROM PRINCE WILLIAM SOUND

Description of Database

A summary of the database of subsurface sediment samples from Prince William Sound collected during Exxon's winter shoreline monitoring program is provided in Table II-1, which lists monthly averages for each of 18 monitoring sites included in the winter program (counting Sleepy Bay central, east, and west separately). The "holes" in the table are indicative of gaps in the monthly monitoring schedule. No samples were taken in February.

While the monthly entries in Table II-1 show a generally downward trend, the direct comparison of monthly averages can be misleading, since a different subset of monitoring sites was visited each month. However, a valid comparison is provided by the last two columns of the table, where the "first" and "last" entries have been repeated for each site. Statistics for these two columns are given at the bottom of Table II-1, where the average, standard deviation, number of entries, and the estimated standard deviation of the average, are shown. The reduction in the averages from the first observations (about 4,500 ppm) to those of the last observations (about 1,400 ppm) is about 70%. Furthermore, these averages are large compared to their estimated standard deviations (about 1,600 and 800 ppm, respectively), which ensures that the observed trend is statistically significant.

These trends were obtained using all 250 samples in the database for sediment samples taken during the winter monitoring program and analyzed at Exxon's Corporate Research Laboratory in Clinton, New Jersey, with the following exceptions:

- 1) Samples of surface sediments (typically 0-5 or 0-10cm deep)
- 2) Bulk oil samples (e.g., oil film taken from a pit)

Table II-1

Summary of TPH Data for All Prince William Sound Sediment Samples From Exxon's Winter Monitoring Program
Monthly Averages of Subsurface Samples by Site

Site	Energy Level	Location	No.	SEP ppm	OCT ppm	NOV ppm	DEC ppm	JAN ppm	MAR ppm	First ppm	Last ppm
AP-1	High	NE Smith Island	20	1455	3072	2175	889		741	1455	741
AP-2	High	NW Smith Island	13	6017	5265		687	944	6017	6017	944
AP-3	High	Little Smith Island	3			62				62	62
AP-4	Low	Foul Pass	14	2247	144		29	459	45	2247	45
AP-5	Moderate	Passage Point	13		1024		31		118	1024	118
AP-6	Low	East Herring Bay	6	208	48			85	60	208	60
AP-7	Moderate	East Green Island	17	247	79			13	3	247	3
AP-8	High	West Green Island	16	20839	1879	7413		1056	14319	20839	14319
AP-10	High	South Point Helen	10	2368	2914			705		2368	705
AP-11	High	NE Latouche A	8	774	336				260	774	260
AP-12	High	NE Latouche B	26	20073	16589	2700	4899	6502	592	20073	592
AP-13C	High	Sleepy Bay Central	14		10792		3683		734	10792	734
AP-13E	High	Sleepy Bay East	10				2195		1275	2195	1275
AP-13W	High	Sleepy Bay West	16			14442		2198	2686	14442	2686
AP-14	High	NW Latouche Island	19	512			304	215	2427	512	2427
AP-16	Moderate	East Elrington Is.	16	174	58			68	41	174	41
AP-17	Moderate	North Elrington	12	78	115		459	131		78	131
AP-18	Low	South Elrington	17	312	279		81	315	43	312	43

Total Samples 250

Average	4657	1399
Standard Dev.	6782	3227
Count	18	18
Std.Dev. of Avg.	1645	783
First/Last Ratio	3.33	
% Reduction	70	

- 3) Composite samples (representing several sampling locations)
- 4) Samples of unknown or uncertain origin

A detailed inspection of this database reveals that, while certain "principal" transects were sampled repeatedly, additional samples were often taken from other transects as well. Also, different portions of the principal transects were sampled at different times, as dictated by timing (daylight) considerations and tide windows. A more consistent dataset is obtained by selecting only samples from the principal transects and omitting samples from the lower intertidal zone which was sampled regularly (and which, generally, contained little oil). The transects for the "transect database" are those transects that were sampled at least once during both the first half (September-November) and the second half (December-March) of the program.

One other data point was omitted from the more limited transect database: Bag #24 at Site AP-8. This sample, taken in March, came from the top of a fine sand that was found under about 1 foot of coarse gravel in the storm berm. Some gravel was included in the sample, but only the sand was analyzed. The field notes indicate that oil had accumulated on top of the fine sand by gravity drainage. The TPH content of the sand was found to be about 41,800 ppm (4.1% by weight); however, being limited to a thin layer, this value was clearly not representative of the general subsurface condition at the site. Other subsurface samples taken in the upper intertidal had less than 1,000 ppm.

Transect Summaries

Table II-2 presents the data for the principal transects in summary form. This reduced, but internally consistent database consists of 162 samples from 18 transects. It contains a total of 65 entries; thus, the database reflects an average of $65/18 = 3.6$ visits per transect, and an average of $162/65 = 2.5$ samples per entry.

The downward trend of the TPH data in Table II-2 is again illustrated by the last two columns where the "first" and "last" observations are repeated for each of the 18 transects. The average, standard deviation, and the estimated standard deviation of the average, are given below each of these columns. The average of the last observations is again much lower

Table II-2

Summary of TPH Data for Selected Transect Prince William Sound Subsurface Sediment Samples From Exxon's Winter Monitoring Program

Monthly Averages for Principal Transects - Excluding Samples from Lower Intertidal

SITE	E	Z T	DIST		No (m)	SEP ppm	OCT ppm	NOV ppm	DEC ppm	JAN ppm	MAR ppm	First ppm	Last ppm
AP-1	H	Tr.7	5 to 27	Average	13		4541	2662	1173		906	4541	906
AP-2	H	Tr.3	11 to 22	Average	6	10614	6830		307			10614	307
AP-2	H	Tr.4	10 to 19	Average	4	1419			24	1233		1419	1233
AP-4	L	Tr.6	2 to 16	Average	12	2247				459	37	2247	37
AP-6	L	Tr.2	9 to 12	Average	2		144			90		48	90
AP-6	L	Tr.4	7 to 12	Average	4	208	48			80	60	208	60
AP-7	M	Tr.6	6 to 20	Average	10	247	55			16	0	247	0
AP-8	H	Tr.8	5 to 20	Average	14	20839	2730	7413		1056	598	20839	598
AP-10	H	Tr.6	16 to 29	Average	8	2368	4342			742		2368	742
AP-12	H	Tr.7	5 to 30	Average	16	20073		3357	5872	823	884	20073	884
AP-13C	H	Tr.17 8-21	8 to 21	11	10792		10792		4602		1094	10792	1094
AP-13W	H	Tr.24 15-24	15 to 24	10	14442			14442		3618	1848	14442	1848
AP-14	H	Tr.2	5 to 12	Average	4	353			55			353	55
AP-14	H	Tr.4	5 to 16	Average	10	824			469	304	2505	824	2505
AP-16	M	Tr.5	2 to 25	Average	13	174	70			65	45	174	45
AP-17	M	Tr.4	2 to 15	Average	8	36	172		600	13		36	13
AP-18	L	Tr.4	6 to 14	Average	7	432			204	60	38	432	38
AP-18	L	Tr.8	7 to 16	Average	10	191	279	20	20	47	48	191	48
Total Samples	162												
										Average		4992	583
										Standard Dev.		6916	703
										Count		18	18
										Std Dev. of Avg		1677	171
										First/Last Ratio			8.6
										% Reduction			88

than the average of the first observations (about 580 ppm versus 5,000 ppm, an 88% reduction).

It should be noted that these estimates are biased on the conservative side by the fact that not all transects were sampled in September and March. In fact, the average time span between first and last sampling for the 19 transects is about five months; hence, the reduction of TPH values observed during the six-month winter program reflects only about five months of natural cleansing.

Trend Analysis

Table II-3 shows the results of an exponential regression (by determining a least-squares linear fit to the logarithms of the monthly averages) for the transect data shown in Table II-2. To facilitate the analysis, the gaps in the data matrix were filled in by geometric interpolation; i.e., each interpolated value is equal to the square root of the product of its two neighbors. The entire column for the month of February was added in this fashion. Missing data points in September and March were added first by assuming a level trend. This preserves the first and last data points for each transect and tends to bias the analysis towards underestimating the rate of natural cleansing.

Summary statistics for the complete (interpolated) data table, including monthly averages, standard deviations, and estimated standard deviations for the averages, are shown in the lower part of Table II-3. The last row of each table shows the exponential regression fit to the monthly averages. It was obtained by fitting a straight line to the logarithms (also shown) of the monthly averages. The exponential trend line and monthly averages are plotted in Figure II-1. The indicated rate of natural cleansing is about 32% per month.

A breakdown by energy level is shown in the bottom plot in Figure II-1, where monthly averages and regression lines are plotted separately for subsurface sediment samples from ten transects on high-energy sites and eight transects from low/moderate energy sites (see Table II-1 for the classification of monitoring sites by energy level). The number of individual samples contained in these subsets is 96 and 66, respectively.

Table II-3

Regression Analysis for TPH Data from Principal Transects
 Note: Data Gaps Filled by Constant Extrapolation and Geometric Interpolation

SITE	E	Z T	DIST		No	SEP (m)	OCT ppm	NOV ppm	DEC ppm	JAN ppm	FEB ppm	MAR ppm	First ppm	Last ppm
AP-1	H	Tr.7	5 to 27	Average	13	4541	4541	2662	1173	1076	987	906	4541	906
AP-2	H	Tr.3	11 to 22	Average	6	10614	6830	1448	307	307	307	307	10614	307
AP-2	H	Tr.4	10 to 19	Average	4	1419	1370	1323	1277	1233	1233	1233	1419	1233
AP-4	L	Tr.6	2 to 16	Average	12	2247	144	59	24	459	130	37	2247	37
AP-6	L	Tr.2	9 to 12	Average	2	48	48	59	73	90	90	90	48	90
AP-6	L	Tr.4	7 to 12	Average	4	208	164	129	102	80	69	60	208	60
AP-7	M	Tr.6	6 to 20	Average	10	247	55	37	25	16	4	0	247	0
AP-8	H	Tr.8	5 to 20	Average	14	20839	2730	7413	2798	1056	794	598	20839	598
AP-10	H	Tr.6	16 to 29	Average	8	2368	4342	2409	1337	742	742	742	2368	742
AP-12	H	Tr.7	5 to 30	Average	16	20073	8209	3357	5872	823	853	884	20073	884
AP-13C H	Tr.17 8-21	Average	8 to 21	10792	10792	10792	7047	4602	2851	1766	1094	10792	1094	
AP-13W H	Tr.24 15-24	Average	15 to 24	14442	14442	14442	14442	7229	3618	2586	1848	14442	1848	
AP-14	H	Tr.2	5 to 12	Average	4	353	191	103	55	55	55	55	353	55
AP-14	H	Tr.4	5 to 16	Average	10	824	683	566	469	304	873	2505	824	2505
AP-16	M	Tr.5	2 to 25	Average	13	174	70	68	67	65	54	45	174	45
AP-17	M	Tr.4	2 to 15	Average	8	36	172	322	600	13	13	13	36	13
AP-18	L	Tr.4	6 to 14	Average	7	432	336	262	204	60	48	38	432	38
AP-18	L	Tr.8	7 to 16	Average	10	191	279	75	20	47	47	48	191	48
			Average		4992	3078	2321	1457	717	592	583	4992	583	
			Standard Dev.		6916	4204	3688	2148	984	699	703	6916	703	
			Count		18	18	18	18	18	18	18	18	18	
			Std Dev. of Avg		1677	1020	894	521	239	170	171	1677	171	
			Log of Avg		3.70	3.49	3.37	3.16	2.86	2.77	2.77			
			Regression		4637	3140	2127	1440	975	661	447			
			Rate of Cleansing (%/month):		32									

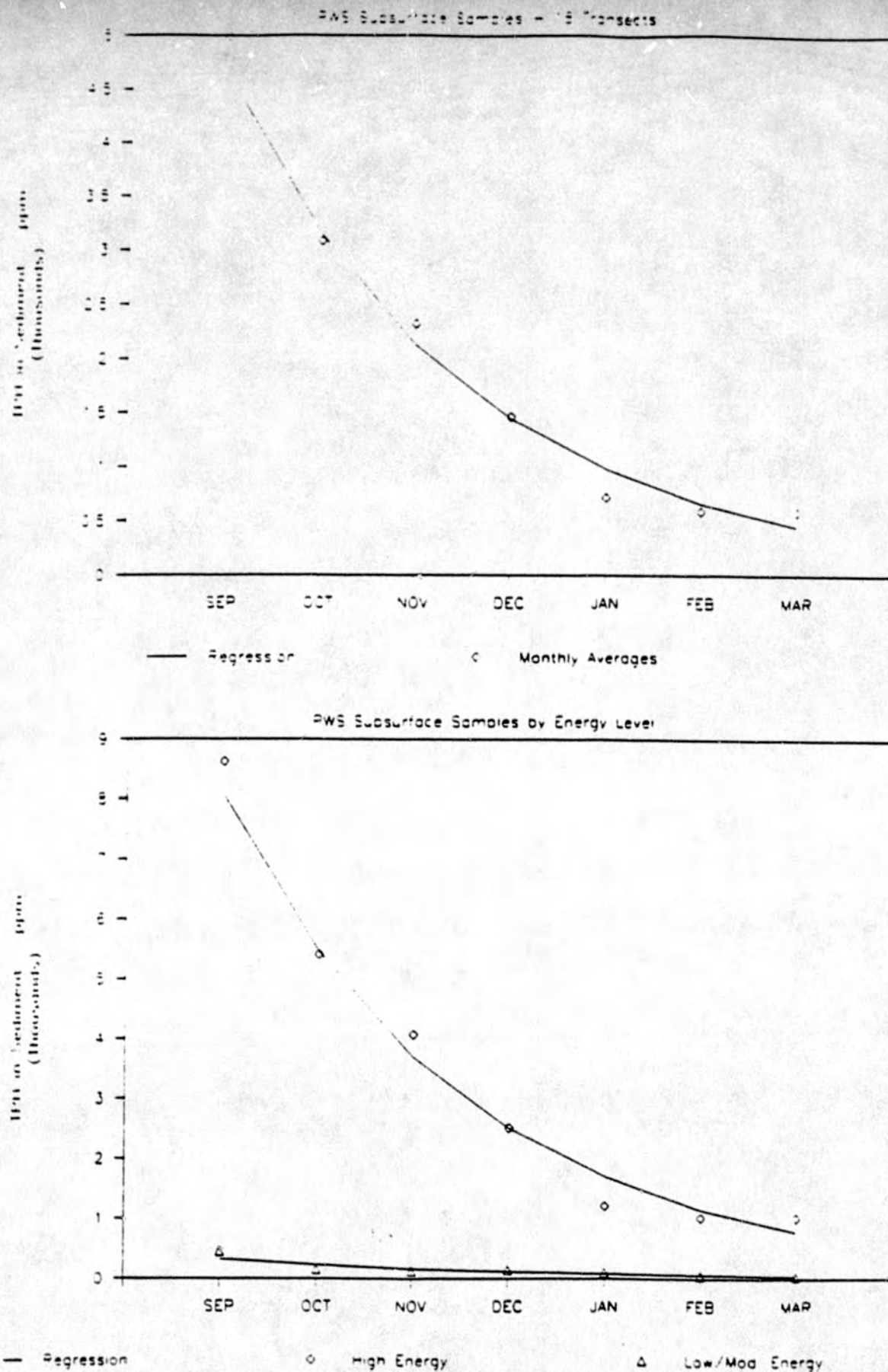


Figure II-1. TPH concentrations in subsurface sediments at 18 Exxon transects in Prince William Sound from September 1989 to March 1990, for all transects and divided into different energy levels.

Conclusion

Subsurface sediment samples from principal transects that were sampled repeatedly during Exxon's winter shoreline monitoring program in Prince William Sound show a strong downward trend in residual oil content. The data indicate that nearly 90% of the oil residue present on these transects in September was removed by natural cleansing during the course of the fall and winter. The estimated rate of reduction in TPH values was about 30% per month during the six-month period from September 1989 to March 1990.

The trend of natural cleansing is most pronounced in subsurface samples from the ten transects on high energy sites. The average TPH content in samples from these transects decreased from more than 8,000 ppm to about 1,000 ppm during the course of the winter. The residual oil content in subsurface samples from eight transects on lower energy sites started out much lower and averaged less than 100 ppm in March.

II.A.2 TRENDS IN NATURAL REMOVAL RATES OF SUBSURFACE OIL

Introduction

Natural cleansing rates for subsurface oil on specific shorelines impacted by the EXXON VALDEZ spill are problematic to predict because of the wide variability in substrate grain size, degree of exposure to wave and tidal energy, depth of penetration of the oil, and weathering of the oil which changes its properties over time. All of these factors contribute in varying amounts to determine the fate of subsurface oil at any one locality. However, it is possible to predict the persistence of subsurface oil based on studies of previous spills, as well as what has been learned from field observations and laboratory studies on the behavior, composition, and changes in the amount of oil in subsurface sediments in Prince William Sound over time.

There have been two recent reviews of the persistence of oil and recovery rates following oil spills in cold water environments. Marshall and Gundlach (1990) conducted a review of the literature focusing on the actions and environmental recovery of past spills which were similar in setting, oil type, and expected types of impacts to the EXXON VALDEZ spill,

for NOAA. Baker et al. (1990) conducted a similar review, focusing on the natural recovery of cold water marine environments after an oil spill and including resource-specific analyses, for Exxon. These two reports are good sources upon which to base a synthesis of the oil persistence trends on shorelines that are potential candidates for rock washing in Prince William Sound. The reader is referred to these documents for a detailed review of oil-spill case histories.

Predictions for Alaskan Shorelines

In attempting to use previous case histories to predict the persistence and toxicity of subsurface oil in Prince William Sound, there are several factors which are specific to Prince William Sound and Prudhoe Bay crude oil which either speed up or slow down known processes.

Those factors that speed oil removal rates are:

- 1) Flocculation is a natural process whereby very fine-grained mineral sediments interact with oil residues on sediments and seawater to form a solids-stabilized emulsion which adheres less strongly to the sediments. The emulsion is formed when polar components in the weathered oil residue are attracted to the electrically charged surfaces of fine mineral particles such as clays and silts in the presence of salt water. The formation of these emulsions have been observed in the field and studied by Exxon in laboratory experiments (Bragg et al., 1990). Field observations in Prince William Sound over the winter/spring indicate that the subsurface oil in the upper 10-30cm is less sticky, brown in color, and readily smears off sediments, whereas deeper oil is still very tacky, more black in color, and overall fresher in appearance. Obviously, flocculation rate or effectiveness is a function of the volume or thickness of oil on individual grains and in pore spaces. The importance of emulsion formation is that it provides an additional mechanism for removal of oil from subsurface sediments. Also, flocculation may reduce the potential for formation of asphalt pavement by subsurface oil residues. Many of the case histories cited in the two reports note that the longest-term persistence of oil was in the form of asphalt pavements which contained relatively undegraded oil. However, flocculation has not been quantified as to its effectiveness under field conditions.

2) Biodegradation has been shown to be progressing at rapid rates in Prince William Sound because of the existence of naturally occurring hydrocarbon degrading bacteria. Although the degradation rates are slower with depth, removal of oil by microbial processes is an important mechanism that will speed the removal of subsurface oil at the EXXON VALDEZ site in comparison with past spills.

3) The extent of removal of surface oil during the 1989 treatment. In many of the case histories, the formation of surface pavements led to persistence of both surface and subsurface oil. The formation of pavements in Prince William Sound was significantly reduced by the extensive use of cold- to hot-water flushing of the shoreline in 1989. The SSAT data show that asphalt pavements are generally small and isolated, and they are being removed manually in 1990.

Those factors which slow subsurface removal rates include:

1) Relatively low wave energies relative to grain size of shoreline sediments. In Prince William Sound, the sediments are disproportionately coarse grained in comparison to the annual distribution of wave energy. That is, much of the shoreline sediments are residual rather than depositional. Large, storm-generated waves occur intermittently, therefore making it difficult to predict when sediments are likely to be reworked to the depths of residual oil. Thus, physical removal of deep subsurface oil by abrasion during sediment erosion and deposition cycles is not likely to occur quickly. In effect, we have an unusual condition whereby coarse-grained, porous sediments occur in an area which is not reworked to significant depths by frequently occurring storms. Therefore, most case histories are not directly applicable.

2) The initially high degree of contamination of some of the shorelines. Many of the natural removal processes, such as biodegradation, flocculation, etc., have rates which are a function of the loading of oil. Heavy loadings lead to greater retention times. Many of the shoreline areas under consideration for rock washing are those areas which were most heavily contaminated.

With these factors in mind, an attempt was made to predict the persistence of subsurface oil in different exposure settings. Reports of previous spills seldom specifically mention subsurface oil; rather, residual oil is referred to as tar, asphalt pavements, or crusts. For example, at the

ARROW spill in Chedabucto Bay, which is one of the best studied analogs for the sheltered regions of Prince William Sound, Vandermeulen (1977) reports that, "...tar stranded along the mid-water line on high- and medium-energy beaches has a self-cleaning half-life of around one and a half to two years. However, this half-life is increased by a factor of at least 10 where the Exposure Index drops such as with oil stranded on low-energy shores..." Figure II-2 shows summary curves on self-cleaning rates by wave exposure from Vandermeulen (1977). At the METULA site, asphalt pavements were found at sheltered localities 6.5 years (Gundlach et al., 1982) and 12.5 years (Owens et al., 1987) after the spill. At the Baffin Island Oil Spill (BIOS) project, long-term monitoring of an experimentally oiled beach showed that less than 10% of the original stranded oil remained after 18 months of open water (six years), based on a consistent database (Humphrey et al., 1990). This study represented a worst-case scenario for a low permeability beach in a sea-ice, cold climate, low-energy environment.

In Prince William Sound, natural removal has effectively cleaned the upper 10-30cm of sediments in areas of moderate to high wave energy. Although the data are highly variable, there have been reductions in the deep subsurface oil levels as well. Whereas there are not yet enough data to draw long-term curves for self-cleansing rates for the subsurface oil which remains as of 1990, the times required for removal of oil from all shorelines to background levels are predicted as follows:

<u>Area</u>	<u>Residence Time for Oil Buried in Gravel Beaches</u>
1) Sheltered parts of Prince William Sound	10+ years
2) Sheltered outer Kenai	3-5 years
3) Exposed parts of Prince William Sound	2-4 years
4) Exposed outer Kenai	1-2 years

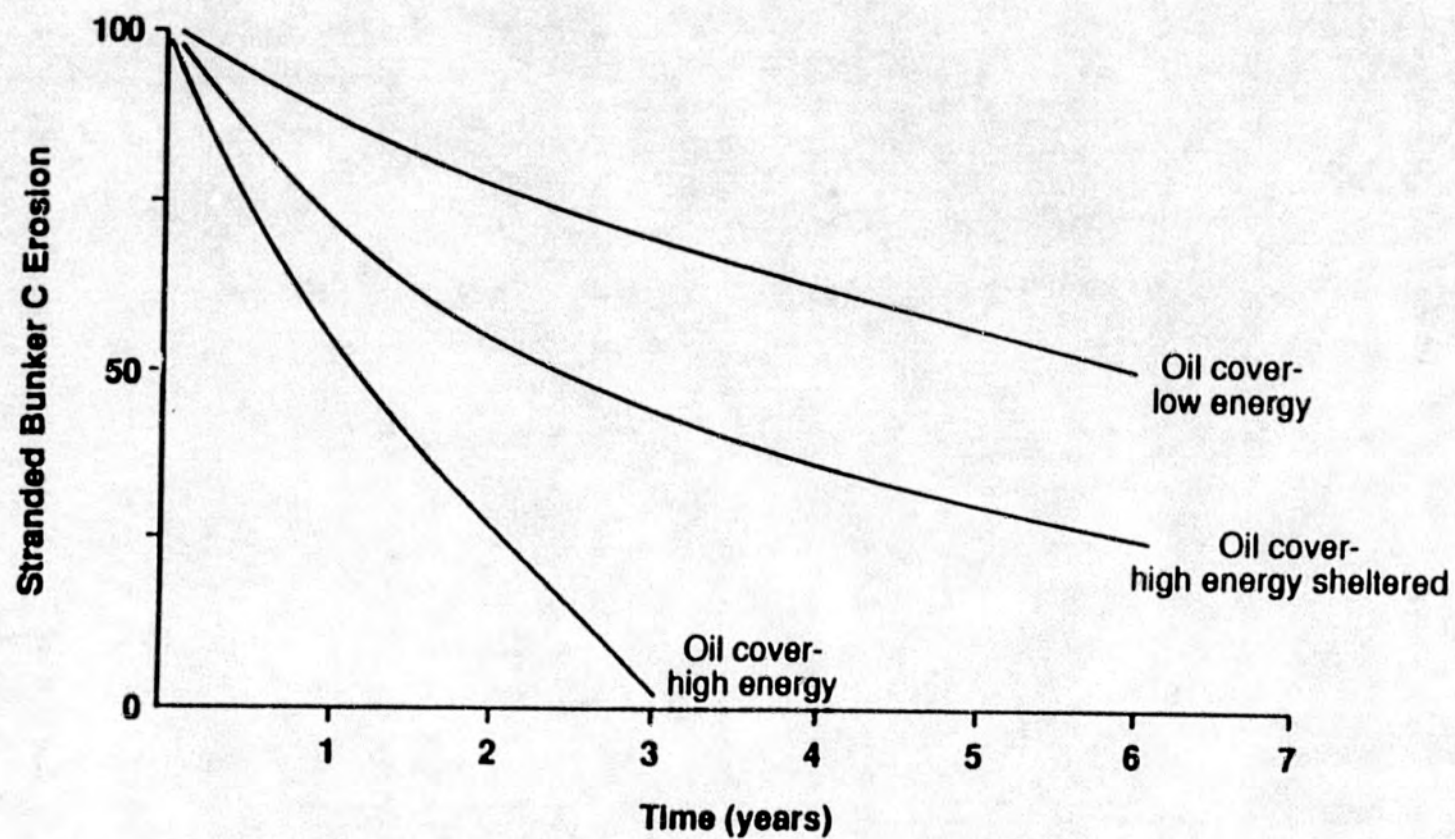


Figure II-2. Summary of oil spill self-cleaning processes (modified from Vandermeulen, 1977).

These estimates are based on the assumption that no other treatment is attempted for removal of subsurface oil, such as berm relocation.

Exposure of Subsurface Oil by Wave Action

One of the processes of natural cleansing is the physical abrasion of the oil during sediment reworking by storm waves. There is concern that the subsurface oil will be exposed during shoreline erosion, thus extending the period of impairment of use. Although there are limited data upon which to draw conclusions, the following observations made during the winter monitoring program are applicable.

The set-aside on northeastern Latouche Island, LA-15, is a good example of how subsurface oil might be exposed because it was never treated. This site was monitored monthly by NOAA from September 1989 until February 1990 and again in May 1990. By November 1989, the surface oil had changed from 100% of a heavy coating on the cobbles to a spotty, thin stain. After November 1989, scattered cobbles that had 100% of a heavy coat were observed along the profile; these oiled cobbles had been reworked from a deeper zone into the surface sediment layer. This process occurred gradually with the passage of storms. It is expected that, during major storms, there could be a pulse of oiled cobbles mixed into the surface sediments. As observed at LA-15, because the exposure occurs during storms, these oiled cobbles are rapidly reworked and diluted. With time, the available source of oiled clasts in the subsurface will be diminished, and exposure will decrease. Only the larger clasts are expected to remain oiled after exposure; the smaller sand, granules, and pebbles will be cleaned by abrasion during the storm event. At the two candidate beaches, these processes have already cleaned most of the oil from the surface sediments even at Sleepy Bay which is more sheltered but has finer-grained sediments.

It is not anticipated that subsurface oil exposed during storms will include extensive asphalt pavements. Many of the subsurface oil deposits are not concentrated enough to form pavements; the oil occurs mostly as coatings on clasts. Pavements are mostly surface deposits, although pavements at the high tide zone could be covered by recent deposition of clean sediments. The beaches in Prince William Sound are not subject to

large-scale erosion/ deposition events during normal storms. Therefore, major exposures of subsurface oil would occur only during major storms.

Reapplication of Fertilizers

The reapplication of nutrient fertilizers during the Summer 1990 cleanup is generally expected to enhance the natural degradation of both surface and subsurface stranded oil. Oxidative biodegradation is a key process in the natural removal of petroleum in the environment. Microorganisms (e.g., bacteria, fungus, etc.) utilize the oil as a carbon source (food) in conjunction with oxygen and nutrients to produce carbon dioxide, water, and additional biomass. The target goal is to accomplish in one year what would be three to four years of natural biodegradation. To achieve this level of enhancement, the fertilizer needs to be reapplied every four to six weeks to maintain an adequate nutrient levels to keep the microbial population at an optima growth rate. In addition to nutrient availability, temperature and micro-nutrient availability must be at growth maxims to achieve the targeted rate of enhancement.

The two major fertilizer products being applied are Inipol and Customblen. Inipol is being used for surface treatments only while Customblen is targeted for use for both surface and subsurface treatments often in conjunction with Inipol. The actual enhancement to subsurface degradation has not been well quantified due to variability of field measurements between the treated and non-treated control stations from the Summer of 1989 studies. Visual observations from field studies as well as laboratory studies indicate that enhanced degradation is occurring through the use of bioremediation.

A detailed study to test the relative benefits of fertilization application is currently being conducted in Prince William Sound. The study will focus on the stimulation of biodegradation achieved by the addition of fertilizers, the toxicity associated with the application of fertilizers, and the potential eutrophication affect from the use of fertilizers. Preliminary results show evidence of increased mineralization rates on treated beaches of up to three times those on untreated beaches. Toxicity testing of water samples collected over the application area during the first tidal flooding showed no toxicity to mysids. The results of this study will be used to decide if fertilizer reapplication will take place.

II. A. 3. EFFECTS OF SUBSURFACE OIL RESIDUES AND PROJECTIONS OF RECOLONIZATION

Introduction

In this section, estimates are made of the probable biological effects of applying no rock washing operations to the subsurface oil and projections are made of the recolonization rate should no rock washing take place at the candidate beaches. These estimates and projections were made by surveying the existing conditions at the candidate segments; reporting observations of oil-related effects as of May 1990; evaluating the relationships between biological effects and concentrations of oil in beach materials; evaluating oil spill effects and recolonization rates at other previous spills; and using existing information to project recolonization rates.

The estimates of continuing effects and of the recolonization rates are clearly speculative, since there is no way at this point to empirically test these effects. Also, the high degree of variability in the density and kinds of organisms that inhabit Prince William Sound beaches precludes the determination of absolute estimates of effects and recolonization. All of the following projections must be recognized as best professional estimates, based upon past experience.

Estimated Effects of Oil Remaining in the Beach: Sleepy Bay Segments LA-17/18/19

Most of the intertidal biota in Sleepy Bay live either upon rock or cobble/boulder surfaces or under them to a maximum depth of 5 to 10cm. Therefore, they generally are not in direct contact with subsurface oil that is 10cm deep or greater. Only large, burrowing or tube-forming clams or echinurid worms would have the potential for contacting oil 10cm deep or greater. No large clams or echinurid worms were observed in Sleepy Bay and it is unknown if they occurred there before the spill.

In places where subsurface oil residues are covered by clean surface sediments, the effects of the oil upon intertidal organisms and recolonization would likely be minimal, unless the clean surface sediments were removed by erosion. In places where subsurface oil is contiguous with surface oil, it is impossible to distinguish the effects of the surface

residues from those of the subsurface sediments. In a moderately exposed pebble/cobble beach, such as that in Sleepy Bay, sediments are continually shifting, thereby alternately exposing and covering different areas. Interstitial water is continually transporting oil from place to place within the beach. Because of these dynamic processes, subsurface oil that is contiguous with surface oil may pose a longer term inhibition to recolonization than the surface deposits alone. Also, since surface oil would be treated along with subsurface oil where they occurred together, it seems obvious to consider the effects of both with regard to estimating biological effects and recolonization.

Some of the limpets, mussels, barnacles, and littorinid snails observed in May 1990 were dead in Sleepy Bay middle and lower tidal zones. About 10 to 50% of the shells of these animals were empty (Section I.C.7), but remained unbroken. In addition, there were many detached dead fronds of *Fucus* and coralline algae among the rocks in the upper tidal zone. The cause of these deaths is unknown. However, it is likely that some proportion of the plants and animals had been killed by the oil some time before the May survey. Most of the delicate shells of *Littorina*, mussels, and limpets that may have been killed by the onset of cold winter conditions late in the fall of 1989 likely would have not survived the winter unbroken and likely would have not remained within the intertidal zone. One moribund clam and one dead mussel with their internal soft parts intact also were observed in May, suggesting that they had died very recently.

Top predators, such as sea stars and *Nucella*, were relatively sparse, as compared to information reported by Rosenthal et al. (1982) for other beaches in Prince William Sound. In May, these animals were absent and in June they were found mainly near or upon very large rocks or rock outcrops from which the oil was quickly removed. Animals that are generally recognized as being sensitive to the effects of oil, such as amphipods and isopods, were generally absent in patches of the upper tidal zone that had high concentrations of oil, but they were often abundant in most areas of the middle and lower tidal zones.

Collectively, the weight of these observations suggest that oil residues that remained in parts of Sleepy Bay in the spring of 1990 were adversely

affecting at least some of the organisms there. These continuing adverse effects clearly are relatively minor in severity and extent.

However, there were encouraging signs of biological recovery, especially in the lower tidal zone. There were many young-of-year mussels, limpets, littorinid snails, nemerteans, *Fucus*, other algae, and barnacles. Egg masses from spawning littorinid snails were abundant. There was an abundance of oligochaete worms in very oily sand and gravel in the high tidal zone, presumably consuming bacteria that have been degrading the oil. Often they were accompanied by small predatory nemerteans and, occasionally, by young littorinid snails and mussels. There were occasional nereid worms, terebellid worms, and gunnels under boulders in the mid-and lower tidal zones. There were gammarid amphipods under boulders in the mid-and lower tidal zones where algal debris had accumulated, along with a few hermit crabs among the boulders. Biological populations observed in June were generally more dense and diverse than those observed in May.

It appears that the epibenthic biota of the lower tidal zone were not as severely impacted by the oil as the epibenthic and infaunal biota of the upper tidal zone. Little or no oil remained in the lower tidal zone in May 1990.

The eelgrass bed in the subtidal zone would be highly susceptible to the effects of the oil (as was observed at the IRISH STARDUST spill in British Columbia), but appears to have survived the spill. The mid-tide zone had a fairly representative community of organisms (as compared to the descriptions of Rosenthal et al., 1982) and the remaining oil, if any, was buried deep in the beach, and, therefore, isolated from the plants and animals above it.

Therefore, it appears that the projected biological effects upon intertidal biota of not treating the beaches may be expressed mainly in the upper tidal zone. This zone normally is not inhabited by a very rich community (Rosenthal et al., 1982) due to desiccation and lack of food. The continuing effects to animals in this zone may be attributable more to suffocation by thick deposits of oil and lack of oxygen than to toxicity. Much of the subsurface oil occurs as shiny, black coatings upon sand, gravel, and pebbles. Much of the low molecular weight fraction of the oil that is most toxic has been removed (see section I.C.3.). Organisms were found living

in high intertidal zone beach samples with up to 16,000 ppm total petroleum hydrocarbons, suggesting that the remaining oil is not very acutely toxic. Based upon the projections forecast in Section II.A.1, subsurface oil residues may remain in the beaches of Prince William Sound for up to 10 years or more. The remaining surface oil in the upper tidal zone will likely dissipate more quickly.

Continued effects upon the biota of the mid-tidal zone and lower zone are not expected to be very severe, since it appears that these zones were not heavily impacted at the outset. Relatively abundant populations of barnacles, mussels, brown, red and green algae were apparent in May 1990. There is no reason to expect that these organisms would be adversely affected by the oil remaining in the intertidal zone. Top predators, such as *Thais* and sea stars, however, were missing from unconsolidated materials in May 1990 but were observed in June 1990, suggesting that they are recolonizing the beach or are highly mobile and able to migrate around the beach over large areas. There is no reason to suspect that the lower tidal zone eelgrass bed would be affected in the future by the remaining subsurface oil in the intertidal zone. In investigations following other oil spills, permanent damage to intertidal communities usually was not observed and recovery of the communities to a status approximating pre-spill conditions was complete in one to six years (Gundlach et al., 1982; Straughan, 1976; Green et al., 1974; Mancini et al., 1989; Nelson-Smith, 1977). However, in a recent report, Dauvin and Gentil (1990) concluded that several species of crustaceans that had been abundant in coarse beaches before the AMOCO CADIZ spill had not yet recolonized the same beaches ten years later, and therefore, biological recovery was incomplete.

If the oil is not removed by rock washing, effects upon organisms in the water column offshore from the beaches are expected to be minor relative to the effects experienced during the initial phases of the spill. Sheens bleeding from the beach in Sleepy Bay could adversely affect the salmon smolts migrating out of the local stream in the spring or the epibenthic zooplankton that these fish depend upon. But, these effects probably would be minor and short-term due to the weathered nature of the oil, the short exposure period, and dilution by the large water mass in Sleepy Bay and adjoining Prince William Sound.

Projected Effects of Oil Remaining in the Beach: Point Helen

The lower tidal zone at Point Helen is dominated by a luxuriant assemblage of large algae, including *Alaria marginata*. There are many sea stars, crabs, gunnels, gammarid amphipods, caprellid amphipods, bryozoans, sponges, and other sensitive species in this assemblage. It does not appear that the oil spill has had a lingering severe effect upon the biota of this zone.

The mid-tidal zone is relatively depauperate. Without baseline, pre-spill data it is not possible to know if this condition existed before the spill. The large boulders in this zone support very few organisms. The gravel/sand matrix under the boulders also supports a relatively depauperate community. Again, it is impossible to know if this condition existed before the spill.

The upper tidal zone has even fewer organisms than the mid-tidal zone, and, again, it is unknown if this condition existed before the spill. The data summarized by Rosenthal et al. (1982) suggest that the upper tidal zone of mixed coarse beaches generally is depauperate. A few littorinid snails and oligochaetes were found in this zone at Point Helen.

Continuing effects of the oil, if left without rock washing, are expected to be minimal or undetectable in the lower tidal zone. It is unlikely that the upper tidal zone normally supports a rich community due to exposure to desiccation, mobility of the beach sediments, and a lack of food among the coarse gravel. Therefore, effects in that zone would be of limited importance since a relatively small number of organisms live there. Projected effects in the mid-tidal zone are difficult to estimate. Since the grade is steep, the boulders are rounded and offer relatively poor shelter, there is a very small amount of fine sand or mud beneath the boulders and the beach is relatively exposed to waves; it is unlikely that many organisms normally live in this zone that would be effected by the remaining oil.

Projected Recovery Rates

In any oil spill, one of the major controlling factors in the recolonization rate of beach sediments not treated by methods such as rock washing is the rate of loss of the toxic components of the oil. In Prince William Sound, the remaining oil has weathered to a considerable extent

and many of the toxic components have disappeared or have been severely reduced in concentration (see Section I.C.3).

At Point Helen, most of the problematic oil exists in subsurface lenses or layers below the relatively cleaner surficial material. These layers of oil are often deeper than the zone that would be inhabitable by intertidal organisms. Therefore, the data from the quantification of oil residues in surficial sediments may overestimate the concentrations to which prospective colonists would be exposed.

An attempt was made to estimate the points in time at which recolonization and full biological recovery would be possible. The estimates were based upon a projection of the rate of loss of oil from the candidate beaches, estimates of the petroleum concentrations in sediments that equal the lower thresholds of adverse biological effects, and projections of the rates of recolonization once the oil concentrations passed below the effects thresholds. The projections were compared with observations at Point Helen and Sleepy Bay of the oil residue concentrations associated with azoic conditions versus those concentrations in which it appeared that recolonization had begun. In addition, these estimates were compared with observations of recovery in case studies at previous oil spills.

In the winter surveys conducted by NOAA and others at several of the candidate beaches, total oil residue concentrations were determined. Mass spectral analyses were performed with 110 samples (surface and subsurface) during the NOAA winter survey. The data from these oil residue analyses are summarized above in Section I.C.3. The concentrations of total oil and of selected hydrocarbons in the samples were compared with the concentrations known to be associated with biological or toxicological effects in soft-bottom sediments. No toxicological data are available for many of the substituted, high molecular weight hydrocarbons commonly found in the weathered Prince William Sound oil. Data are available from Long and Morgan (1990) for some of the aromatic hydrocarbons, however, they generally do not constitute a large proportion of the total weathered oil in the Prince William Sound beaches.

Comparisons of Hydrocarbon Concentrations with Effects Thresholds

The likelihood of continuing toxic effects of the oil that remains in the beaches can be estimated by comparing the hydrocarbon concentrations

known to be associated with biological effects and the concentrations observed in the candidate beaches. If the ambient oil concentrations are below the toxic thresholds, it is reasonable to assume that continued effects of the oil would be minimal or not expected.

Apparently, there are no data from spiked sediment toxicity tests performed with weathered Prudhoe Bay or north slope crude oil to use as guidance for establishing what concentrations are significantly toxic to marine organisms. Given the lack of these data, information assembled (Long and Morgan, 1990) from other types of studies were used as an estimate of the hydrocarbon concentration commonly associated with adverse effects. These data were supplemented with the matching observations made in May 1990 by NOAA and chemical characterization of samples collected in February and May 1990.

Long and Morgan (1990) reviewed the data from many different studies in which chemical concentrations in fine-grained sediments were associated with measures of adverse biological effects and, based upon these data, offered some guidelines for use in the evaluation of sediment chemistry data. Included among the analyses that were evaluated were total polynuclear aromatic hydrocarbons and many individual aromatic hydrocarbons. The data evaluated by Long and Morgan (1990) are not strictly comparable to the data available for Prince William Sound. The Prince William Sound beaches are largely mixtures of pebbles, cobbles, and boulders with very few fine-grained particles, whereas the data evaluated by Long and Morgan (1990) often were from harbors and bays with muddy sediments. The weathered residues of the oil spilled in Prince William Sound have relatively few low molecular weight aromatic hydrocarbons and few pyrolytic hydrocarbons, whereas the examples reviewed by Long and Morgan (1990) often included relatively high proportions of these compounds. Nevertheless, by using the data base assembled by Long and Morgan (1990), the range in concentrations of hydrocarbons commonly associated with toxic effects can be estimated and compared with the Prince William Sound data on a qualitative basis.

There are no data available from the literature that identify the toxicity threshold of sediment-bound Prudhoe Bay or north slope crude oil. However, the concentrations of individual petroleum constituents can be compared to the effects thresholds with the caveats listed above in mind.

One of the major components of the weathered oil in Prince William Sound is phenanthrene. At concentrations between 0.1 and about 0.2 ppm, no effects attributable to phenanthrene were observed in most studies (Long and Morgan, 1989). At concentrations of 0.3 ppm or greater, effects were almost always observed or predicted. In a bioassay in which clean sediments were spiked with phenanthrene, an LC50 of 3.68 ppm was observed among amphipods. Long and Morgan (1990) suggested that 260 ppb (about 0.3 ppm) phenanthrene may be an overall effects threshold. Rounding 0.3 ppm to 0.5 ppm, toxic effects in sediments generally have been associated with phenanthrene concentrations of about 0.5 ppm or greater. Twenty of the 110 samples from the NOAA winter studies program analyzed by gas chromatograph had phenanthrene concentrations of 0.5 ppm or greater. Neither of the two samples collected in the winter NOAA surveys at Point Helen or at Sleepy Bay exceeded 0.3 ppm. Azoic conditions were found in two samples from Sleepy Bay that had 33 and 1 ppm phenanthrene and 12 samples populated by some organisms had 1 ppm or less phenanthrene. Two of the May 1990 samples from Sleepy Bay analyzed exceeded 0.3 ppm (Table I-2).

Toxic effects generally have been associated with naphthalene concentrations of 0.5 ppm or greater in sediments (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 0.01 and 0.1 ppm naphthalene, compared with 12 samples that had organisms living in them that had 0 to 0.001 ppm naphthalene. Out of 110 samples collected in the NOAA winter surveys, 99 had naphthalene concentrations of 0.01 ppm or less, far below the apparent toxicological thresholds. Three of the samples had 0.110 to 0.2 ppm naphthalene, the highest concentrations observed. None of the samples collected in Sleepy Bay or at Point Helen exceeded 0.2 ppm (Table I-2).

Toxic effects in sediments generally have been associated with fluoranthene concentrations of 1.0 ppm or greater (Long and Morgan, 1990). Effects have not been observed in association with concentrations of about 0.3 ppm or less. Two samples from Sleepy Bay that were azoic had 1.4 and 0.02 ppm fluoranthene, compared to 12 samples that had 0.05 ppm or less and had some organisms living in them. Out of the 110 samples analyzed in the NOAA winter survey, all but one had 0.240 ppm fluoranthene or less. None of the samples collected in Sleepy Bay or at Point

Helen exceeded 0.5 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 1.0 ppm (Table I-2).

Toxic effects in sediments generally have been associated with pyrene concentrations of about 1.0 ppm or greater (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 2.0 and 0.1 ppm, as compared to 12 samples that had living organisms in them that had 0.06 ppm or less. All but one of the 110 samples analyzed in the NOAA winter surveys had pyrene concentrations of 0.420 or less. None of the samples collected in Sleepy Bay or at Point Helen exceeded 1.0 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 1.0 ppm (Table I-2).

Toxic effects in sediments generally have been associated with chrysene concentrations of about 0.9 ppm or greater (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 13 and 0.5 ppm chrysene, as compared to 12 samples that had organisms living in them and 0.4 ppm or less. Eight of the 110 samples analyzed in the NOAA winter surveys had chrysene concentrations that exceeded 1.0 ppm. None of the samples collected in Sleepy Bay or at Point Helen exceeded 0.5 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 0.9 ppm (Table I-2).

From these comparisons of the selected, individual, hydrocarbon concentrations that have been associated with biological effects and the concentrations of these compounds that remain in the Prince William Sound beaches, it appears that relatively few of the samples have concentrations that would be expected to be toxic. This conclusion must be tempered by the fact that there are no toxicological data for many of the hydrocarbons in the weathered Prince William Sound oil associated with sediments. These hydrocarbons, many of which are substituted compounds, may or may not be toxic (they probably are not very toxic).

These chemical data represent the amount of oil adhering to pebble, cobble, and sand particles sampled from intertidal beaches. Since the oil was often adhered to the beach material in a coating, these concentrations may not accurately represent the amount of oil to which potential colonists would be exposed. The concentration data probably overestimate the amount of oil to which organisms are actually exposed. The dissolved, liquid, and semi-solid phases of the oil probably represent a larger threat to the health and viability of colonists. However, data are not available for these phases of oil in the Prince William Sound beaches. Therefore, the

estimates of recolonization rates and recovery must necessarily be based upon an evaluation of the thresholds in effects expected for the oil concentrations on these beach materials.

The rate of recolonization of heavily oiled beaches is very difficult to predict on a site-specific basis, since many complex factors will influence the process. Some of these factors include the natural small-scale patchiness in the texture, slope, and exposure of the beach; the abundance of surviving organisms; the rate of loss of the oil components; and the season during which the concentration of the oil becomes sufficiently low to allow survival of colonists. The net effect of all of these factors would be accelerate or inhibit recolonization. The degree of influence of any one of these factors relative to the others would differ on a case-by-case basis.

Table II-4 includes a summary of case histories on biological recovery rates following oil spills. More detailed discussions of these case histories are included in Appendix A. These case histories were used to make estimates of recovery rates for the No Further Treatment consideration.

In the preparation of the projected recovery rates, it was assumed that the most resistant species would either survive the oil spill and/or they would recolonize the beaches first. Also, it was assumed that the most sensitive species would successfully recolonize the beaches later in the process. In addition, it was assumed that the successional stages in recovery that would be expected at a disturbed unoiled beach would also apply to an oiled beach, once the toxicity of the oil was abated. Finally, it was assumed that the epifaunal species that would be expected to recolonize large stable boulders and rocks would colonize them more quickly than the ambulatory and infaunal species would colonize the interstices of the beach materials. This assumption is based upon the expectation that the removal and detoxification of oil would be more rapid on solid substrates than in the spaces among beach materials.

High-Energy Beaches (e.g., some portions of KN-405)

Some Prince William Sound beaches with a relatively high degree of exposure to wave action were heavily oiled by the initial advances of the oil spill. In some cases, oil penetrated well beneath surface layers at these beaches.

Table II-4

Summary of Biological Recovery Rates for Various Types of Disturbance

NAME	DISRUPTION	BEACH TYPE	DEF. OF RECOVERY	RATE OF RECOVERY	REFERENCE
(1) METULA spill, Strait of Magellan	Arabian crude & Bunker C crude oil	Mixed sand/gravel beaches; some mud sand tidellats	Species richness & abundance	5 Months-initial damage investigated, 2 yrs-not significant; 5 5 yrs -very little; 6 5 yrs - new vegetation	Marshall & Gundlach, 1990 Straughan, 1976 Gundlach et al., 1982
(2) Arrow Oil Spill Chedabucto Bay, Nova Scotia	Bunker C oil	Rocky outcrops, eroding till cliffs, gravel, mixed sediment beaches	Self-cleaning bio-recovery; species abundance; biomass measurements; numbers of certain species	After 6 years: more species/biomass at control sites than at oiled sites, clams reduced greatly	Marshall & Gundlach, 1990 Thomas, 1978 Vandermeulen, 1977
(3) General M.C. Meigs oil spill, Washington	Navy Special fuel oil	Intertidal shallow rock shelf & margin of Wreck Cove; coarse sand beaches	Visual/assessments of organisms compared to unoid sites; chem. anal of tissue hydrocarbons recovery by natural processes	General decline in abundance with exceptions; 3 to 5 years	Clark et al., 1978
(4) Irish Stardust spill 1973	1000 Second Fuel Oil; 200 tons	Mixed habitats in embayment	Return of pre-site dominant species	Minor biological recovery appeared to be underway approx 1 yr after spill	Green et al., 1974
(5) US Air Force Fuel Depot Spill 1971	JP4 jet fuel & No.2 heating oil; 14 tons	Intertidal zone Long Island Cove	Sediment analysis of hydrocarbons as well as clam tissue analysis--absence or low levels would be recovery; mortality assessments	6 yrs. shows slow recovery & animals only found in well-drained upper intertidal zone; clams also had significant levels of hydrocarbons in tissues	Mayo et al., 1978
(6) Irini Oil Spill, Sweden 1970	Medium & heavy fuel oil 1000 tons	Bay habitat in Stockholm Archipelago	Recovery determined by survival and health of species showing normal development	Littoral community recovered during period of 1971-1976 6 years	Marshall & Gundlach, 1990

Recovery at oiled beaches of this type will be subject to the same general considerations important at other impacted beaches of Prince William Sound, including the rate of reduction in levels of petroleum hydrocarbons, interactions among intertidal populations after the spill, and the occurrence and relative abundances of constituent species. The greater degree of wave and weather-related exposure at these locations has three major implications for assessment of recovery for the intertidal community impacted by oiling. First, intertidal portions of exposed coastlines are generally less productive than more sheltered shorelines of similar physical character, as it is more difficult for populations of some species to establish themselves and survive on open coasts where heavy wave action frequently mobilizes the beach sediment. As a result, the more fragile representatives of the Prince William Sound intertidal zone may be absent from these more exposed beaches. Second, the greater degree of exposure will facilitate more rapid weathering of oil remaining on or in the substrate and significantly reduce the role of the oil as a potential toxicant. Third, the dynamic and less stable nature of exposed shorelines makes evaluation of "recovery" difficult, as variability is more pronounced and comparison to "normal" conditions more complicated.

Similar to the situation observed by Gundlach et al. (1981) after the AMOCO CADIZ spill, oiled portions of exposed shoreline in Prince William Sound may be rapidly recolonized by algal species such as *Fucus*. The acute toxicity of the oil that initially came ashore, as well as cleanup techniques employed at many of the impacted beaches, may have removed a large portion of the herbivorous components of the intertidal community, such as littorine snails. This selective exclusion would enable algae to quickly spread, possibly recolonizing an area to a greater degree of cover than had existed prior to the spill. However, as was found by Southward and Southward (1978) following the TORREY CANYON spill and cleanup, recovery of the herbivore populations resulted in a return to conditions that could be termed normal, or near-normal.

Because the presence and toxicity of oil at exposed beaches can be expected to be decreased due to accelerated weathering, biological recovery rates at these locations are likely to be fairly comparable to those for recolonization of new or denuded substrate (see subsequent discussion in section II.B.2). Total time for recovery to conditions approximating a pre-

spill community would also be expected to be similar to that observed for other spills, or three to five years. However, the relatively lower diversity and abundance in the exposed shoreline intertidal zones suggests a less complex recolonization process, and may result in a slightly reduced time of two to four years. By these estimates, it is possible that by 1991/1992, exposed beaches may have, to a large extent, recovered. Recent observations at sites of this type suggest that recovery is well under way and may be more rapid than that at other beaches.

Moderate-Energy Beaches (e.g., portions of LA-18)

Based upon the available information, it appears that recolonization is predicted to occur relatively quickly in the stable oiled beaches in which loss and weathering of the oil is proceeding and in which an abundant intertidal community is expected. These beaches are undergoing weathering and loss of oil through natural processes and/or with the help of surface washing and bioremediation. They are beaches that are sufficiently stable to allow the successful attachment and survival of plants and animals. The beach materials are not mobile, do not roll in the waves and offer refuge for potential colonists. Indeed, the recolonization process appears to have begun in these beaches as of May 1990.

The recolonization of these beaches by intertidal species with intermittent and infrequent recruitment is impossible to predict; these species may not reappear for five to 30 years. O'Clair and Zimmerman (1986) observed that some large clams were very slow in recolonizing some beaches in Alaska following the nuclear bomb tests. Therefore, predictions of recovery are based upon the recolonization rates expected for the "core group of dominant species" that typically inhabit these habitats, as generally described by Rosenthal et al. (1982).

It is very likely that the recovery of the epibenthic fauna and flora will be quicker than that for the infauna. The plants and animals attached to the upper surfaces of large boulders and rocks often survived the initial oil spill and will proliferate in the subsequent absence of oil. Some of the sensitive echinoderms killed by the oil will not provide a predatory control of these species.

Recolonization of resistant species is predicted to proceed quickly during the spring and early summer of 1990 as the oil concentrations

diminish and as the normal seasonal cycle of spawning and recruitment takes place. The colonization of the beaches likely will reach an intermediate plateau during the fall and winter of 1990. During this plateau, the community likely will be composed of a core of resistant indigenous species such as epifaunal barnacles, snails, mussels, marine algae, ambulatory snails, nemertean worms, oligochaete worms, and a few resistant crustaceans, such as shore crabs and hermit crabs, and infaunal polychaete worms. During the following spring of 1991, it is expected that some of the more sensitive species of the community, such as certain copepods, amphipods, and isopods, will be successful in recolonizing the beaches. By the following fall (1991), a community composed of many of the same species and with small-scale variability similar to that of pre-spill conditions will exist. In the subsequent years, it is expected that the most sensitive species and juveniles of the adults that colonized the beaches in the previous years and many of the top predators will inhabit the beaches in numbers similar to pre-spill conditions in the spring of the third year (1992). This pattern of spurts of recolonization followed by plateaus of relative stability probably will continue for several years.

Therefore, re-attainment of the abundances of the core group of dominant species similar to those of pre-spill conditions ("recovery") is expected to occur in about three to five years. Generally, recolonization of oiled beaches by a community more or less similar to that of pre-spill conditions has occurred in three to six years in most spills similar to the EXXON VALDEZ (Table II-4). Replacement of pre-spill dominants by other species and the very slow arrival of infrequent spawners have been recorded.

Sheltered Beaches (e.g., some portions of LA-17)

Some beaches that were relatively highly productive in the intertidal zones were heavily oiled and remain heavily oiled. The beaches remain saturated with oil in some patches, including materials at or near the beach surface. They usually have a relatively high percent of small gravel, sand, or finer material, and, therefore, have retained much of the initial loading of oil. These beaches also had a relatively productive community of mussels, barnacles and algae attached to large stable boulders; worms, snails, crabs and tidepool fishes moving around the beach; and some

relatively abundant populations of sensitive crustaceans. They likely are important sources of prey species for salmon and other important resources.

In these beaches, the recovery period is predicted to be somewhat longer than in the beaches in which the oil concentrations are diminishing rapidly. The concentrations of remaining oil are patchy. In many samples, the concentrations of individual hydrocarbons were below known effects thresholds, while in other samples these concentrations equalled or exceeded the thresholds. Some successful recolonization has occurred before and during the spring of 1990, but some parts of the beach are populated only by a few of the more resistant species and some parts are azoic. These opportunist species may competitively exclude later potential colonists, and, therefore, further delay the development of a normal community. Sensitive species are not expected to colonize oiled portions of the upper tidal zones of these beaches in appreciable numbers in the first year after the spill. Additional numbers of the early opportunists may arrive in the spring of 1991, along with a few additional species. The recolonization process will likely occur in spurts each subsequent spawning season, followed by a plateau each fall/winter. Depending upon the rate of loss of the oil, the time to recovery of a community that resembled that of pre-spill conditions may be about five to eight years. Observations made at other spills with similar conditions, indicate that recovery of heavily oiled gravelly beaches required five to ten years. The time required for biological recovery was longer in fine-grained beaches than in coarse-grained beaches.

The time required for infrequent and intermittent spawners is impossible to predict; it may be five to 30 years. Fortunately, many of these species are large predators, relatively mobile, and possibly relatively resistant to the effects of oil. Therefore, they may have survived the effects of the oil spill and remain upon the oiled beaches or remain in deeper water and will invade the intertidal zones from below.

II.A.4 SHEENING—FREQUENCY, VOLUMES, PERSISTENCE

Introduction

Determining the volume of petroleum oil in sheens in Prince William Sound is a difficult problem due to observational and logistical factors. Limitations include the difficulty in describing the size of sheens (which may be very irregular in shape), and their thickness (which is indicated by the observed color of the slick). Although NOAA has published a guide relating sheen thickness to color and some standard descriptive terms, this standard is not uniformly used by all observers reporting on sheen occurrence. ADEC observations are reported in different terms than Exxon observations, making direct comparisons between these two sheen reporting systems difficult.

In addition, naturally generated slicks may be difficult to distinguish from those due to petroleum oil, and fuel spills from vessels are common. Exxon states that they have taken samples of "doubtful" sheens and have analyzed them to determine if their spectral signature indicates it is Alaska North Slope crude oil. Exxon reports sheens containing North Slope crude oil or of indeterminate source as one category, separate from sheens associated with vessels, biological activity or other identified sources. The ADEC data does not discriminate sheens in this manner.

Logistical considerations also confound the issue in that weather may limit flight and visibility conditions so that observations cannot be made on a daily basis. Further, the entire Prince William Sound may not be covered on every reconnaissance flight. These factors result in a non-uniform distribution of observation periods, with many days of no observations.

Data Sources

Two primary sources of sheen data were used in this analysis:

- 1) Exxon 1990 Sheen Data in Prince William Sound. This is a listing of "...the sheen sightings reported by the Exxon sheen surveillance crews during 1990 through June 15, 1990," summarized in Figure II-3.

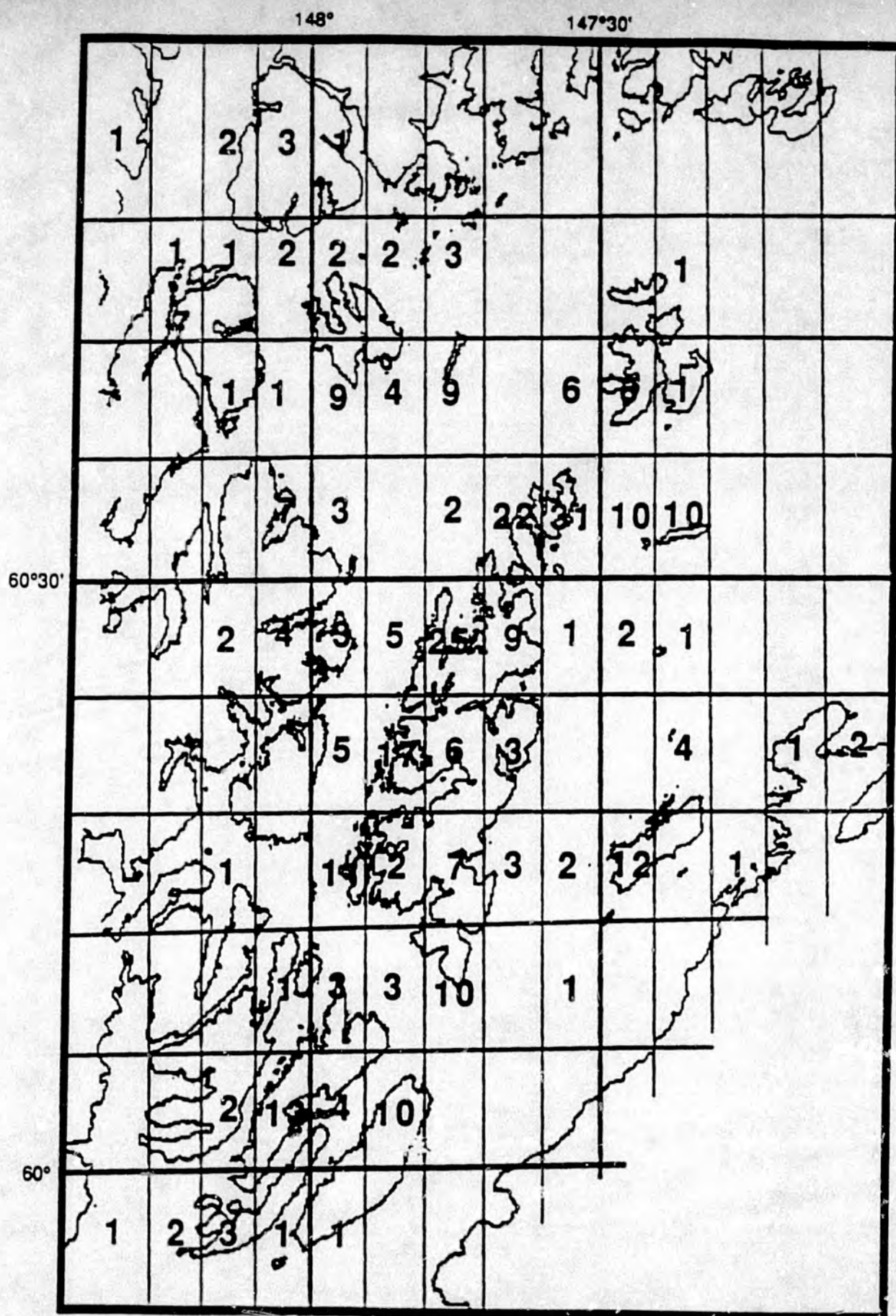


Figure II-3. Sheen sightings reported in 1990 by Exxon crews, through 2 June.

- 2) ADEC Oil and Equipment Tracking computer printout labeled "Sheens reported from 11/1/89 to 4/30/89," subsequently updated to 6/28/90.

Analysis

During discussions in May 1990, ADEC representatives stated their concerns that unless all the subsurface oil were removed from the beaches, there would be continuing potential to generate sheens. It was observed that in recent flights the number of sheens had been more limited than in earlier flights. It was suggested that the impending spring tides would significantly increase the sheening. An expected correlation with high-wind events was also discussed.

As a result of these discussions, the daily number of sheens reported in the ADEC data were plotted along with daily tidal range (highest high minus lowest low tide) and average daily wind speed (summarized into daily mean wind speeds from the Seal Island meteorological station) for the period 14 November 1989 through 6 March 1989 (see Figure II-4). Visual inspection of this plot indicates that there is little correlation between reported sheen frequency and either tidal phase or average daily wind speed for that period. However, there may be combinations or thresholds of wind and tide conditions that result in mobilization of oil from the shoreline. Few sheens are reported during low-wind periods.

The Exxon sheen data are listed by geographic coordinates. Figure II-3 shows that the highest density of sheen sightings was in the vicinity of Eleanor Island and the northern part of Knight Island. Of the all sheens reported in Prince William Sound, 28% were within the six tenth-degree squares centered on Disk Island. Seven percent of the sheens were reported in the vicinity of Sleepy Bay and Point Helen.

Sheen Volume Calculation

Number of sheens provides one estimate of potential risk to water-surface organisms and uses. Another measure is the volume of oil contained in the reported sheens. The volume of oil in sheens observed by Exxon and ADEC was calculated by multiplying the length and width of the sheen by a layer thickness estimated on the basis of reported sheen color.

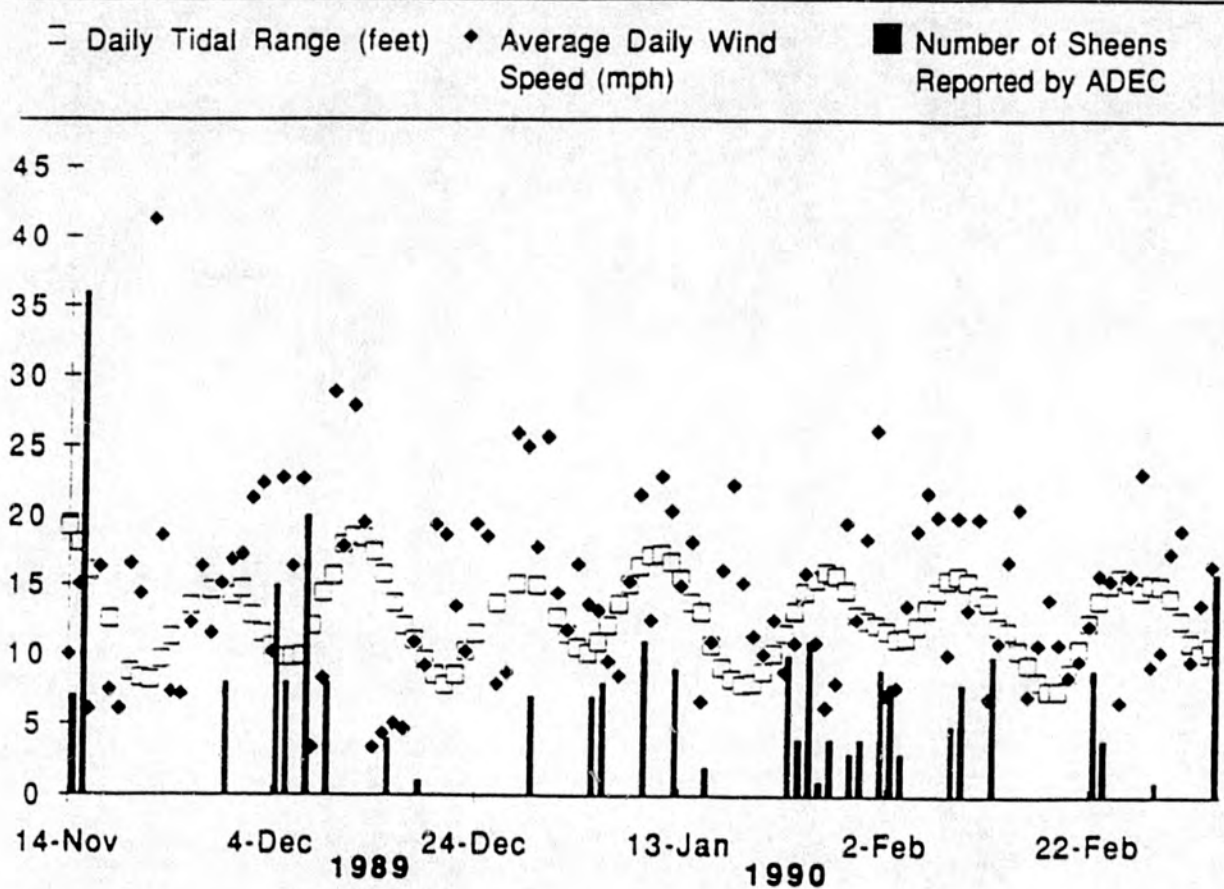


Figure II-4. Plot of average daily wind speed, tidal range, and number of sheens reported by ADEC during the four-month period beginning 14 November 1989.

The following conventions are used for relating sheen color to oil layer thickness:

<u>ADEC*</u>	<u>Exxon*</u>	<u>Thickness (mm)</u>
Gray	Very light sheen (transparent)	.00005
Silver	Silver sheen	.00010
Blue	First color	.00015
Rainbow	Rainbow	.0003
Copper	Dull	.001
	Yellow brown	.01
Brown	Light brown	.1
Black	Brown black	1.0

The Exxon data described the color of observed sheens in terms which are consistent with, but slightly conservative relative to, the NOAA-published Oil Spill Observation Glossary which relates color to approximate sheen thickness. The ADEC sheen color terms listed above were correlated with Exxon sheen colors because ADEC's color convention was not related to sheen thickness. Since observation flights did not occurred every day, sheen volumes were totaled on a weekly basis.

A scatter plot of the weekly totals from the Exxon data indicates that since March 1990 the volume of petroleum in sheens observed in Prince William Sound has decreased logarithmically (see Figure II-5A). Approximately every month the volume decreased by an order of magnitude. According to Exxon data, the amount of North Slope crude oil in Prince William Sound sheens was three quarts or less per week for each of the five weeks since mid-May 1990.

Analysis of the ADEC sheen data followed that of the Exxon data and the weekly values were plotted (see Figure II-5B). The trend in these data is less clearly defined, perhaps due to the inclusion of some non-North Slope crude oil sheens in the data. However, the data confirm that the volume of oil in observed sheens is relatively small.

The apparently rapid decrease of volume of North Slope crude oil in observed sheens throughout Prince William Sound suggests that, in general, the potential for further risk to water-surface resources and uses

* Personal communication John Wilkinson, Exxon; personal communication Tim Langdon, ADEC

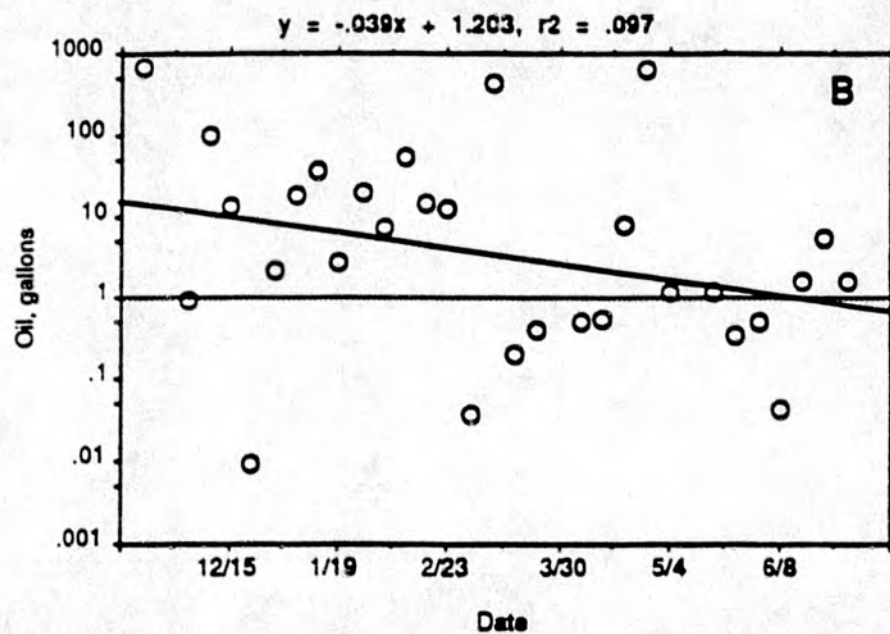
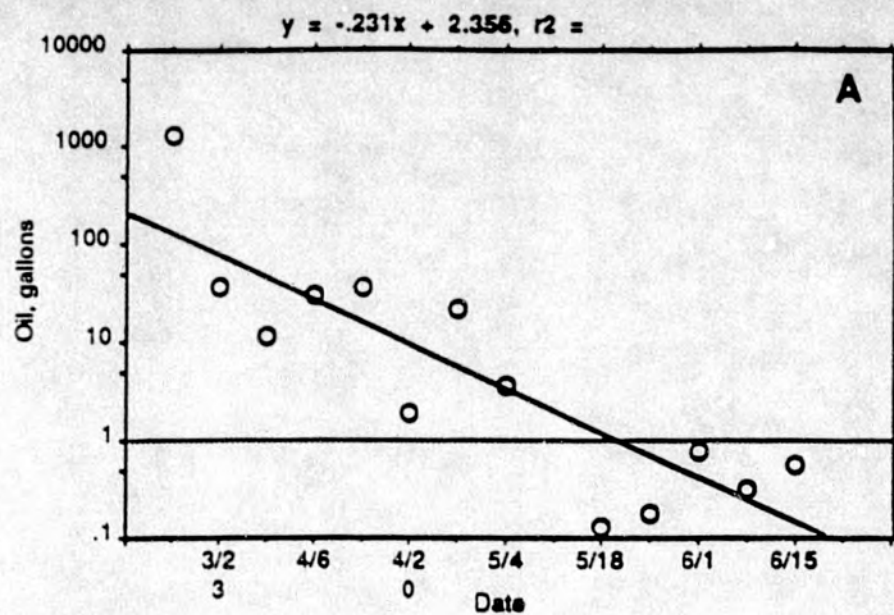


Figure II-5. A: Weekly sheen oil volumes based on Exxon data.

B: Weekly sheen oil volumes based on ADEC data. Note difference in coverage dates relative to the upper plot.

has decreased significantly over time. Both the number of sheens and, more importantly, the volume of this oil contained in sheens are currently very low. Additionally, Exxon's data show that since mid-April oil from the EXXON VALDEZ has contributed only a small portion to the sheening in the Sound (see Figure II-6).

Although intuitively one would expect that high tidal range and high winds would mobilize beach sediments and generate sheens from subsurface oil, existing data do not confirm a simple relationship. The apparent decrease in crude oil sheens can be attributed to the following factors:

1. Decrease in the amount of oil that can be mobilized from the shoreline under normal conditions.
2. Decrease in storm intensity and wave energy resulting in less reworking of upper beach face sediments.
3. Weathering of the oil and removal of the components which tend to form sheens.

Probably all three factors are contributing to the decrease in number, volume, and persistence of sheens.

Release of Subsurface Oil by Storm Activity

An instantaneous release of all of the subsurface oil in a beach during a major storm event would be the worst-case scenario for generation of sheens from subsurface oil. There is no way of accurately predicting when such a storm might occur. However, one did not occur in the winter of 1989, and it may be assumed that such a storm might be in the 20- to 100-year category (Miles O. Hayes, personal communication).

It is difficult to estimate the volume of oil which would be released during such an event. The total volume of oil in the beach is the maximum amount. As an example, ADEC calculated the amount of subsurface oil in Point Helen, using NOAA estimates of oil content, a shoreline length of 2.8 km, an oiled zone width of 15m, and an oiled depth of 120cm. These calculations resulted in an estimated volume of 1,832 gallons in the top 0-30cm and 19,369 gallons in the interval 30-120cm. If all of this volume of oil

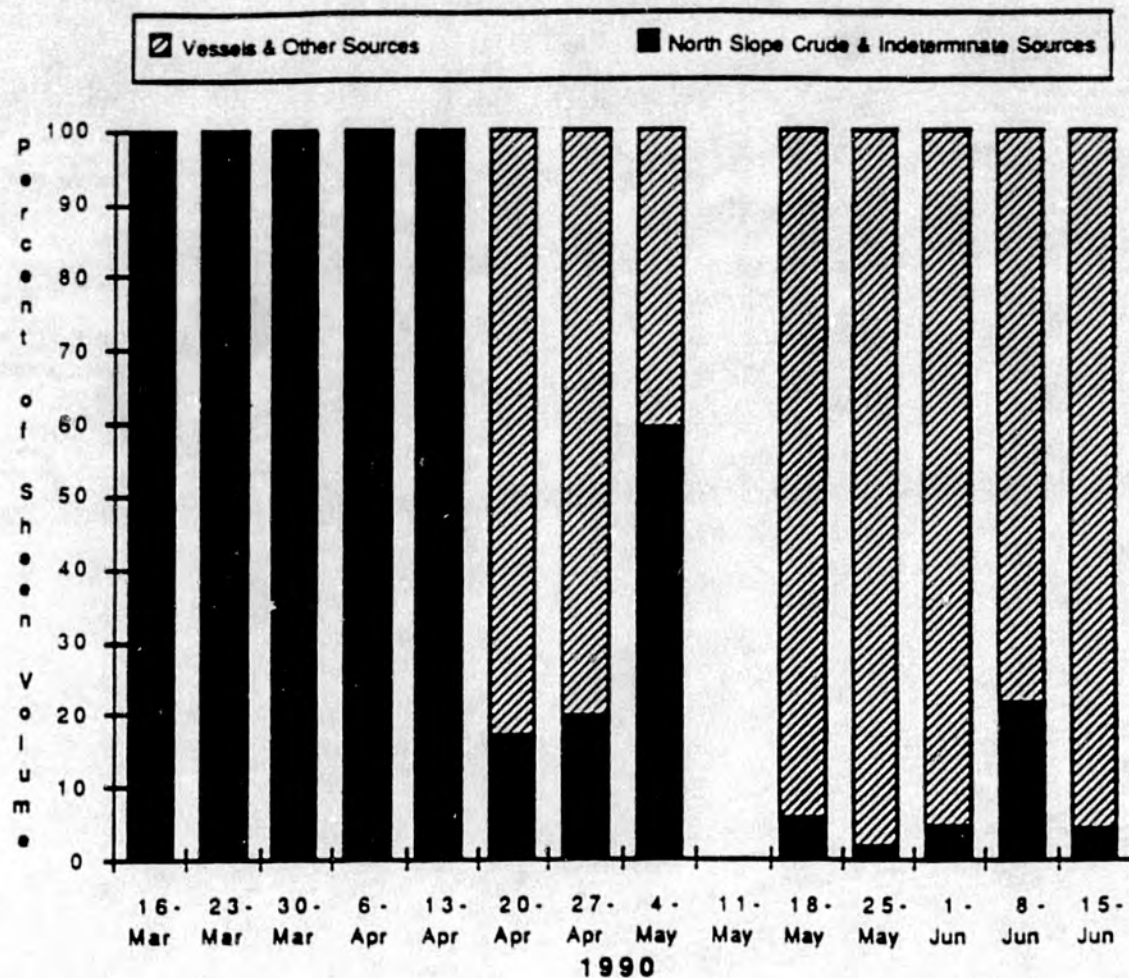


Figure II-6. Weekly sheens in Prince William Sound, as reported by Exxon.

produced a sheen with a thickness to produce the first trace of color, which is unrealistic, the size of the sheen would be 142 square miles.

There is no valid method to estimate the amount of sheen which would be produced from such a storm. After storm occurrences in 1989, oiled clasts appeared at the surface of beaches which had previously appeared clean. This indicates that not all subsurface oil brought to the surface would leave the sediments to produce sheen. Discussion in Section I.C.3. and in the following paragraphs indicates that the concentration of subsurface oil is continuing to decrease, and that the chemical nature continues to change and degrade into a substance with less potential to generate sheen. The storm waves would quickly disperse much of the oil as well. Therefore, only a fraction of the oil in the sediments disturbed by a major storm event would produce sheens. These conclusions are supported by simple field experiments in May and June 1990 at Point Helen and Sleepy Bay. Samples of oiled subsurface sediments from a number of sample pits were placed in the seawater along shore and agitated to see if sheens would be generated. Many times sheens were not evident. On the occasions when sheens were generated, they were observed to dissipate rapidly.

Composition of Sheens

A large number of qualitative sheen samples were collected during October 1989 in bays in western Prince William Sound as part of the Exxon water quality monitoring program. The results of analysis of these samples were published recently (Neff, 1990).

The concentration of total polycyclic aromatic hydrocarbons (PAH: the most toxic fraction in crude petroleum) in the 39 sheen samples collected in October ranged from below the detection limit (about 0.01 parts per billion: ppb) to 18.4 ppb. More than 60 percent of the samples contained less than 0.1 ppb total PAH. The sample containing 18.4 ppb was obtained from Northwest Bay, a site identified in earlier surveys as having been heavily oiled. A surface water sample collected in Northwest Bay in June 1989 contained 30 ppb total PAHs, probably derived primarily from sheen oil.

By comparison, concentrations of PAHs, measured as chrysene (a PAH compound) equivalents, in sheens collected from the open Atlantic

Ocean near Bermuda (an area of collection of abundant tar balls from heavy tanker traffic in the North Atlantic) were in the range of 0.4 to 3.04 ppb (Knap et al., 1986). These concentrations are considered typical for open ocean waters in the vicinity of heavy tanker traffic.

Careful evaluation of the PAH composition of the most concentrated sheens from bays in Prince William Sound revealed that they contained PAHs from two sources. Most of the PAHs were from highly weathered North Slope crude oil (the spilled oil). However, there were also traces of several PAHs that are found almost exclusively in PAH assemblages produced during combustion of fossil fuels. These PAHs probably were derived from engine exhaust soot. Due to weathering, nearly all the naphthalenes and most of the fluorenes and less alkylated phenanthrenes and dibenzothiophenes were depleted in the sheens compared to their concentrations in the fresh crude oil (Figure II-7). Because these are the most toxic fractions of crude oil, sheens from weathered crude oil are much less toxic to marine organisms than sheens from fresh crude oil. Some of the sheens observed in Prince William Sound during the spring of 1990 were not derived from the spilled oil but were from small discharges of diesel oil or bilge washings (often containing lube oil and hydraulic fluid) from boats. These sheens, having been derived from fresh refined oils, probably contained higher concentrations of the lower molecular weight, more toxic petroleum hydrocarbons than did the sheens of weathered crude oil.

To characterize the composition of the most recent sheens in Prince William Sound, a sample collected by NOAA in May 1990 and positively identified as spilled EXXON VALDEZ cargo oil by fluorescence was analyzed by GC/MS using a target-compound approach used to characterize the stranded oil. Figure II-8 compares the target analysis profile of fresh EXXON VALDEZ cargo oil to a sheen sample collected off of Block Island, EL-1A, in May 1990. Note that this profile comparison is limited to the concentration of target compounds only. If the GC/MS extracted ion chromatograms representing the saturate hydrocarbons (m/e 85) for the same two samples are compared as shown in Figure II-9, major differences in the composition of the aliphatic hydrocarbons are obvious. The sheening oil is much fresher in overall composition.

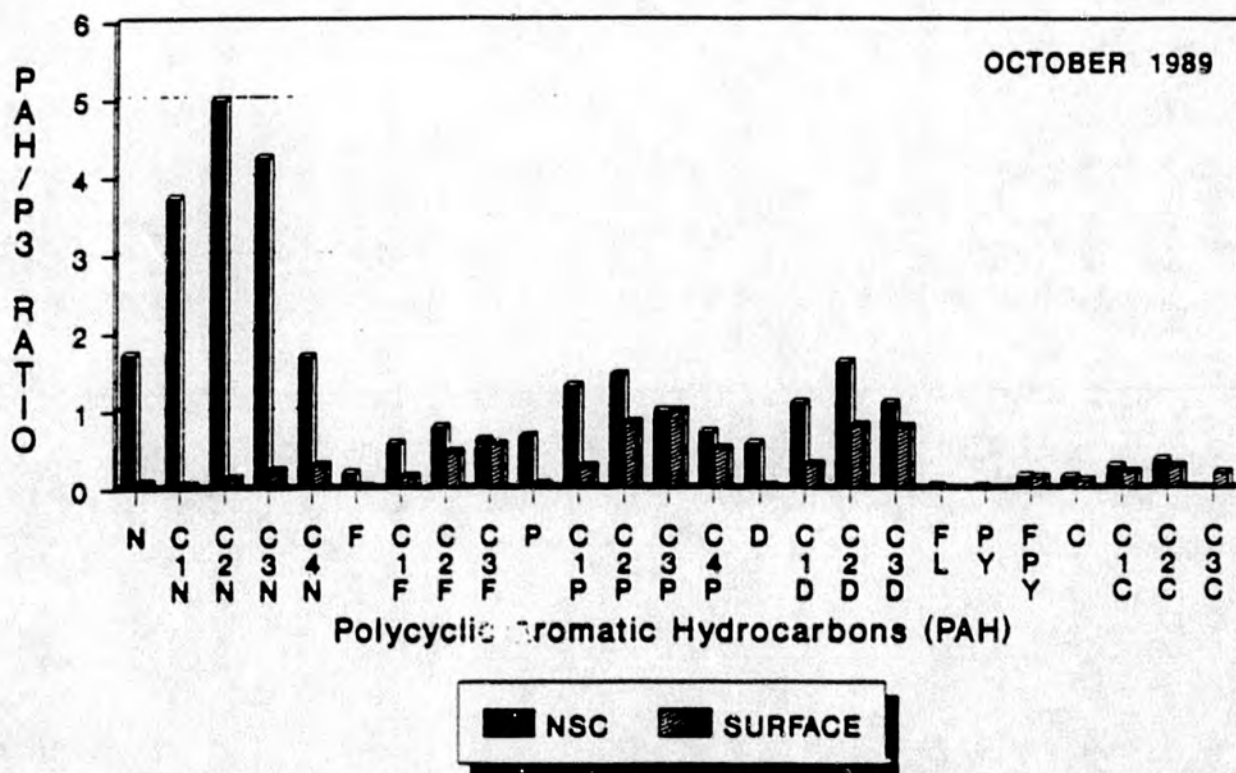
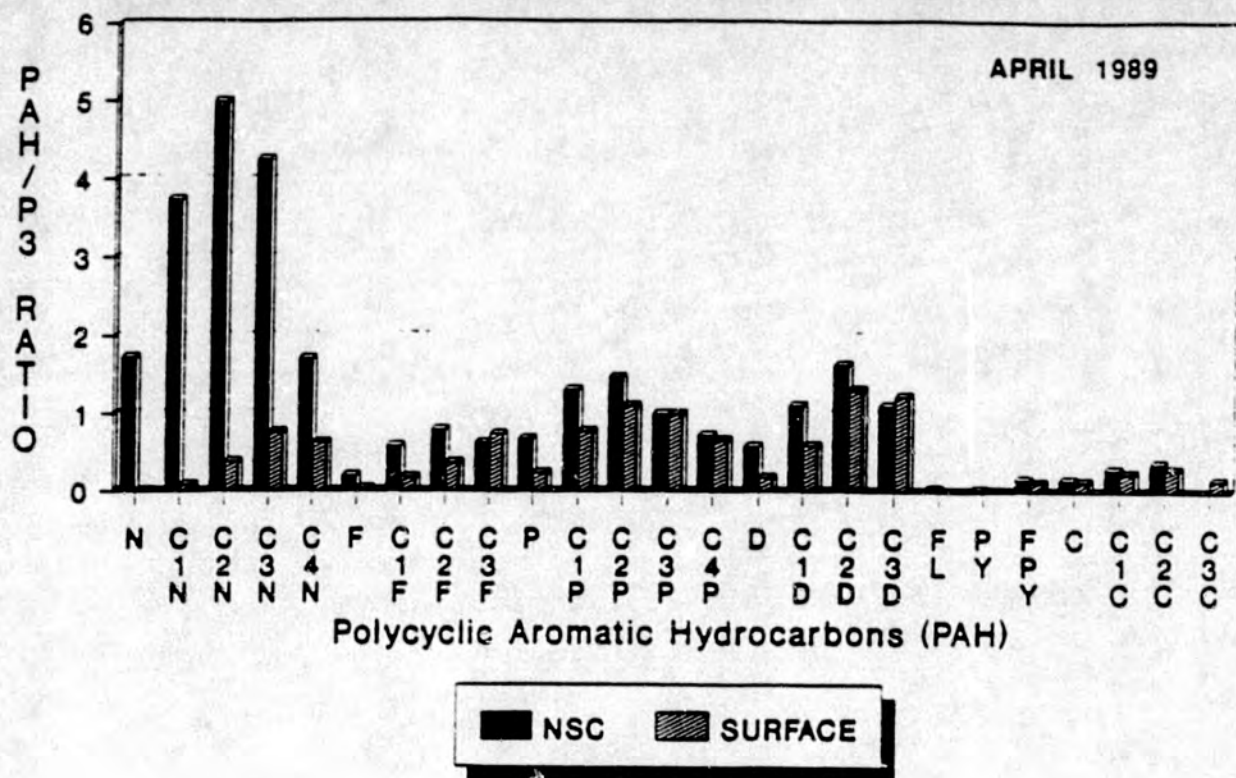


Figure II-7. PAH profiles for North Slope crude oil and sheen oil sampled in the Bay of Isles in April 1989 (upper) and October 1989 (lower).

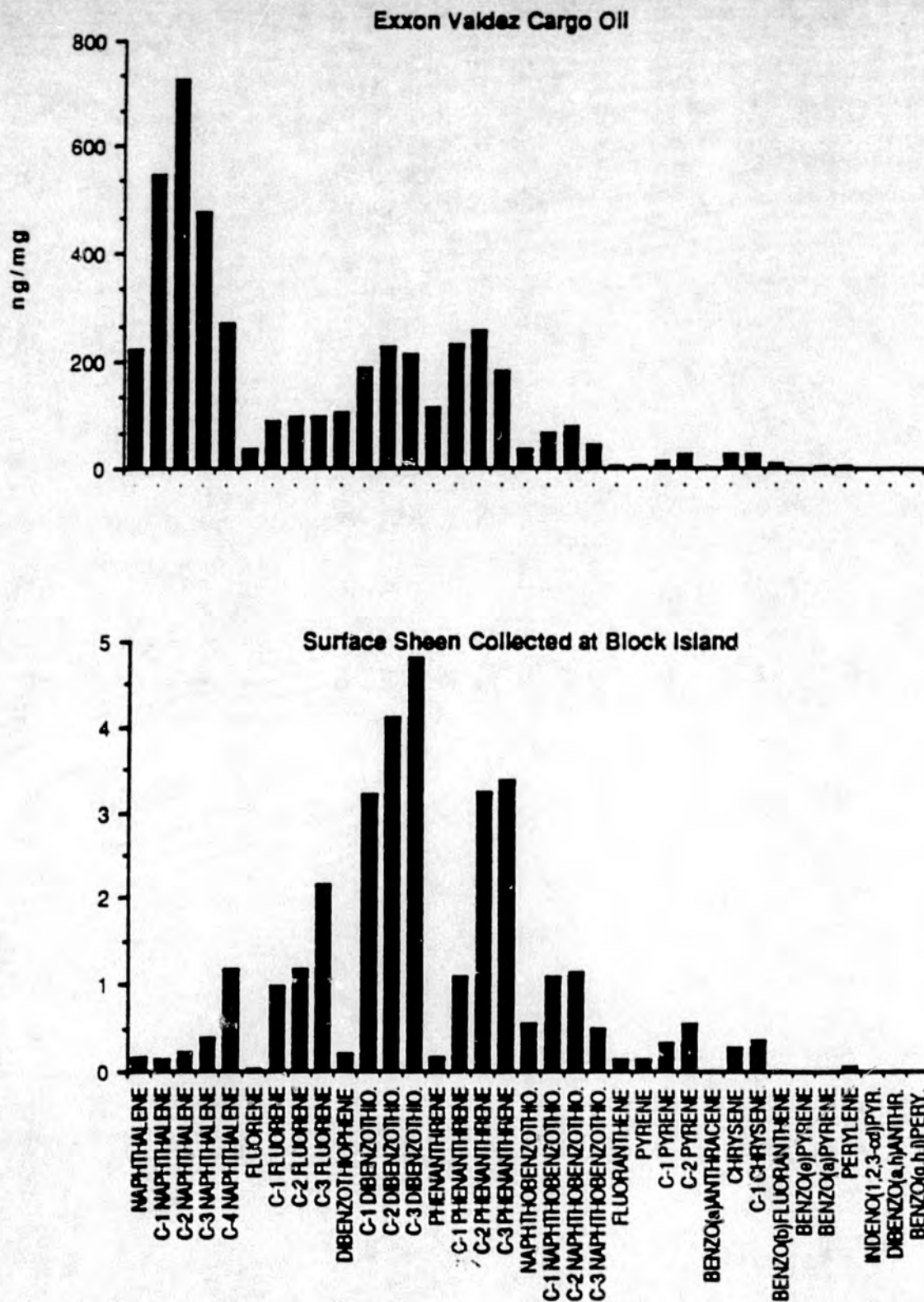


Figure II-8. Comparison of the analysis profiles of Exxon Valdez cargo oil and a sheen collected at Block Island (May 1990).

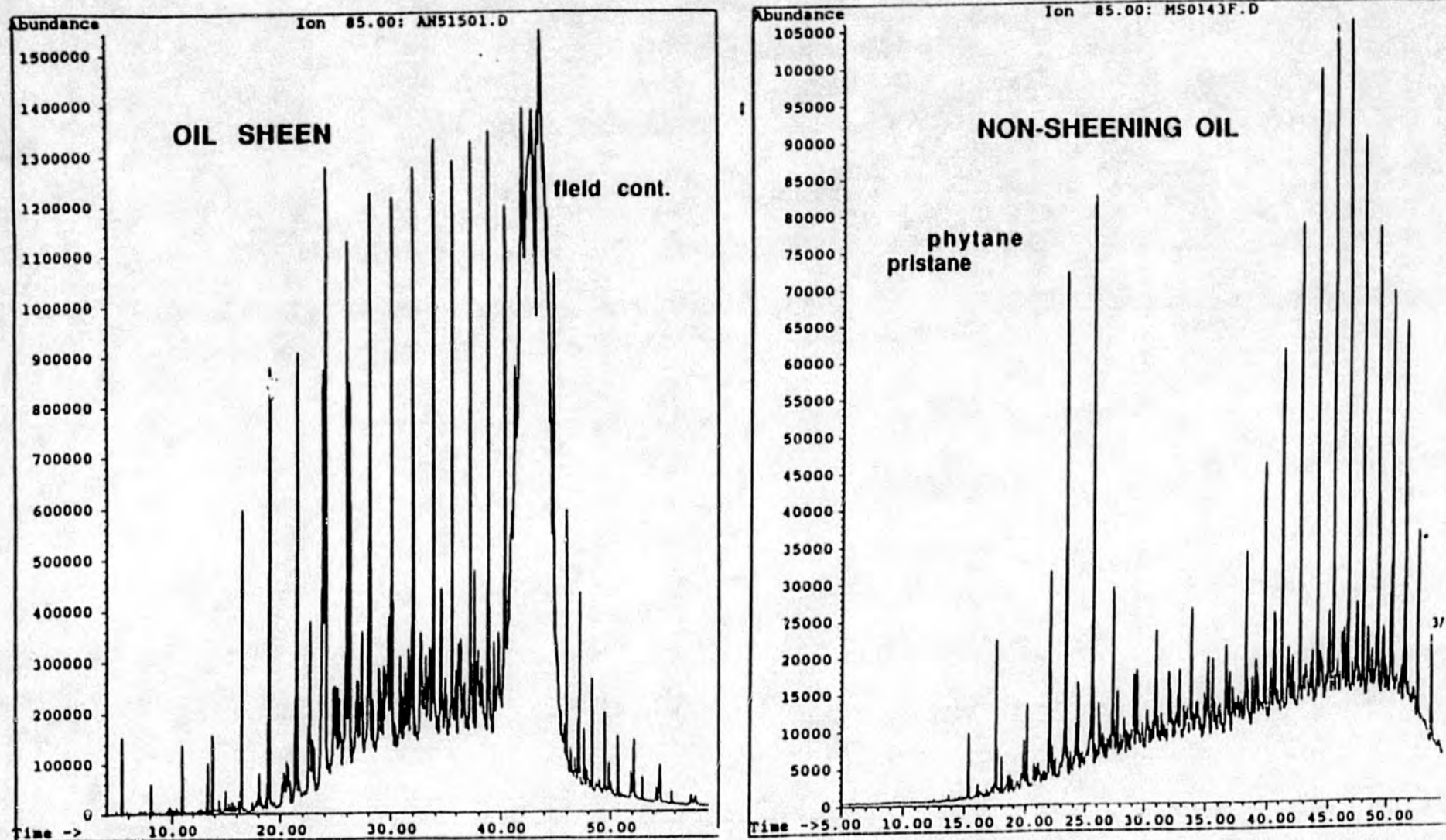


Figure II-9. Comparison of the ion chromatograms (m/e 85) for the sheen sample collected at Block Island and weathered, non-sheening subsurface oil from Sleepy Bay.

The sheen sample did not originate from fresh crude oil, but rather from stranded weathered oil trapped on the beach, which is still capable of producing sheens. When released back onto the surface of the water, the sheen's composition is continually being modified by its interaction at the air-water interface. As the weathered oil sheens, the lower molecular weight constituents are being lost to the atmosphere and water column through evaporation and dissolution. Sheens produced by weathered crude do not persist, but generally dissipate within several hundred feet from shore, probably due to dispersion into the water column.

What is the chemical composition of oil that will sheen? There is some confusion about what oil in the candidate beaches is responsible for sheens. In an attempt to characterize the oil that is a potential concern related to sheen formation, the oil types identified in section I.C.3 were characterized as to their potential to form sheens; comments about sheen formation were included in section I.C.3. These determinations were made either by comments from the samplers or by small microcosm sheen experiments.

The composition of oil that readily sheens is compared to a weathered subsurface oil sample that was identified as non-sheening in Figure II-10. The sample which sheens was collected during May 1990, at US-5 on the Barren Islands. The most obvious difference from this comparison is the presence of the lighter naphthalenes and fluorenes in the sheening oil relative to the non-sheening oil. It is concluded that, in order to sheen, weathered North Slope crude oil must have a significant amount of naphthalenes. The composition of the sheen produced during rock washer excavation operations will be source-oil dependent and be modified rapidly by weathering processes.

Effects On Biota

Weathered oil, such as mousse, tar balls, and deposits of tar and asphalt on the shore or buried in intertidal sediments, can be a source of oil sheens. Concern has been expressed that tidal and rainwater runoff containing sheen oil draining from the upper shore where most of the subsurface oil is concentrated might harm plants and animals living in the more biologically productive middle and lower intertidal zones. These concerns can be addressed from a theoretical basis or from observations of

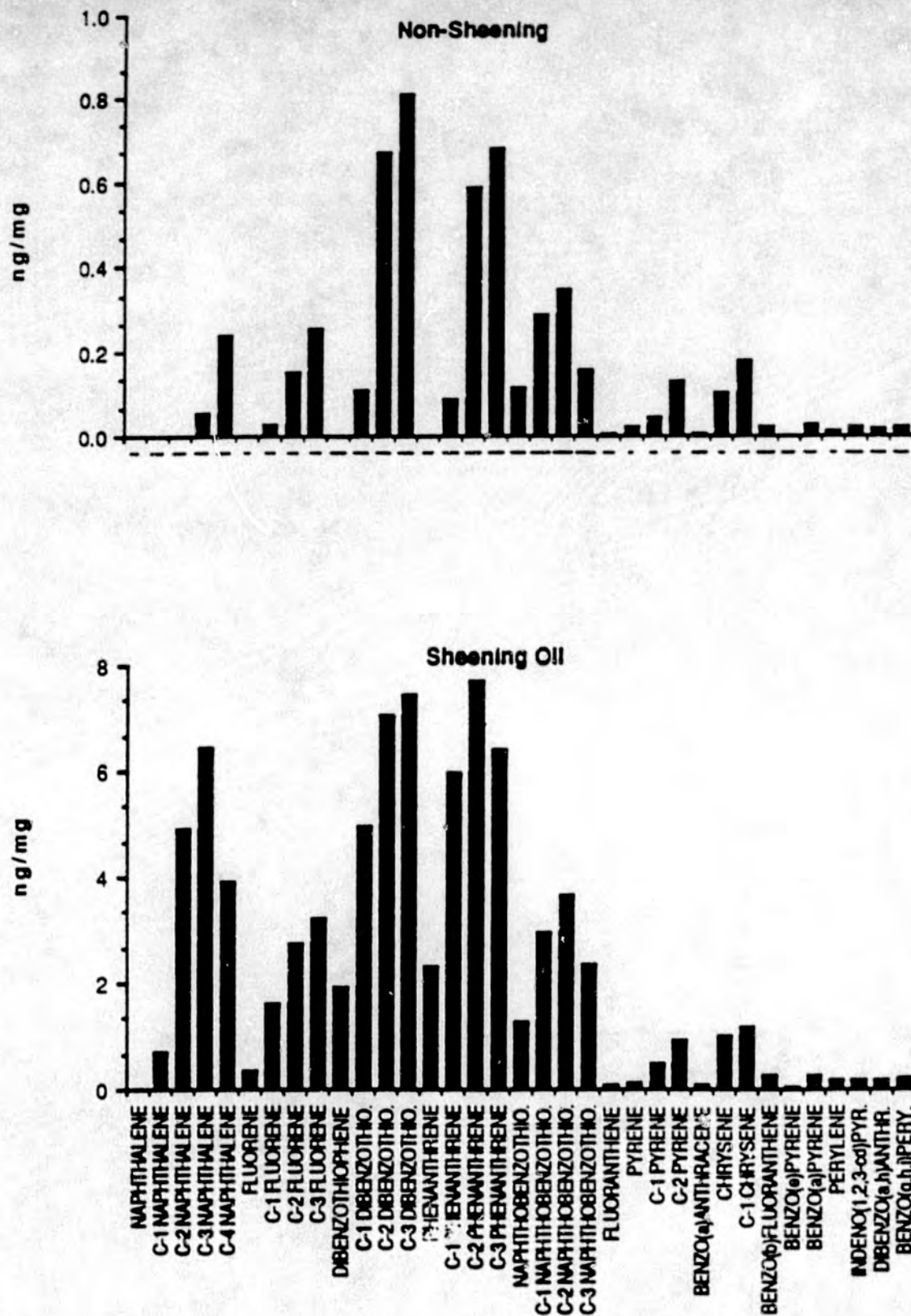


Figure II-10. Comparison of subsurface sediment from Sleepy Bay (non-sheening oil) to a sample collected at the Barren Islands that readily sheens.

the biological condition of shores in Prince William Sound that contain deposits of subsurface oil.

There is strong evidence from the scientific literature (see in particular, Southward and Southward, 1978) that recovery of a rocky shore is much faster if biological communities are only damaged and not wiped out completely by the oil spill and subsequent cleanup effort. The survivors have a strong influence on the rate and course of succession leading to reestablishment of the prespill biological community. Some, but not all, intertidal organisms were killed in the weeks immediately after the spill where the relatively fresh oil came ashore. Some organisms survived on even the most heavily oiled shores, particularly in the more productive middle and lower intertidal zones. There was little evidence of damage to biological communities in the shallow subtidal zone off oiled beaches. Subsequent shoreline treatment activities killed additional intertidal and subtidal organisms. However, die offs of intertidal organisms declined with time after the spill. This decline in biological effects probably was due to decreases in both the amount and toxicity of the oil as it weathered on or was removed from the shore.

In August, five months after the spill, even the most heavily oiled shorelines supported living biological communities. The species compositions of these communities were similar to those that would be expected on shorelines of similar types in Prince William Sound in the absence of oil. The major difference on most shorelines was a decrease in the abundance of individuals of each species and, in some cases, the absence of a few normally rare species.

Recruitment of key species of intertidal plants and animals to oiled shorelines began during the summer of 1989, continued through the winter, and is still going on, apparently at an accelerated rate, in the spring and summer of 1990, even on shores that still contain surface oil (mainly as patches of mousse or asphalt) or subsurface oil deposits. Visual inspection of the intertidal zone of shores containing subsurface oil reveals the presence of rich biological communities characteristic of the types of shores (wave energy and substrate type) being surveyed. In some places, overall abundance of plant and animal life appeared to be less than on similar but unoiled shorelines during the winter months. This apparent

difference in overall biomass on the shore was much less apparent in April and May of 1990 (Sam Stoker, personal communication).

In many cases, the relative abundance of different species of plants and animals on oiled shorelines is different from that on similar but unoiled shorelines. However, the overall impression is that the intertidal communities are healthy and that ecological succession toward the prespill community structure is proceeding rapidly (Sam Stoker, personal communication).

Theoretical considerations of the behavior of subsurface deposits of weathered crude oil in coarse-grained intertidal sediments (see Sections I.C.3 and 4 on sediment oil content and pore water chemistry and Section II.A.6 on dispersion and flocculation) support the conclusion based on actual observations that biological communities are living in the intertidal zone of beaches that have remaining subsurface oil. To the extent that the remaining subsurface oil can still form sheens, the effects of these sheens on intertidal biota will depend on the duration of contact of intertidal plants and animals with the sheen hydrocarbons and the presence and relative concentrations of the potentially toxic fractions of the oil in the sheens.

When tidal water or freshwater runoff that has come in contact with subsurface oil in the upper shore drains from the intertidal zone of the beach during the falling tide, it may carry with it small amounts of oil in solution or as emulsions with clay-sized particles from the subsurface deposit. When this water emerges on the surface, petroleum hydrocarbons present in it in solution, or colloidal suspension, will have a tendency to leave the liquid phase and form a sheen on the water surface.

However, recent chemical evidence (Section I.C.3) indicates that much of subsurface oil buried in the upper intertidal storm berms on the candidate beaches is weathered to the point that it no longer readily forms a sheen. Concentrations of petroleum hydrocarbons, in particular the more toxic PAHs, in interstitial water of oiled sediments are very low (Section I.C.4). In addition, flocculation of weathered oil with clay-sized particles forms stable flocs (Section II.A.6) that probably will not readily disaggregate to form a sheen. Therefore, the likelihood that subsurface oil deposits in the upper intertidal zone of oiled shores are an important source of oil sheens is low, and will continue to decrease as the oil continues to weather.

Intertidal and shallow subtidal plants and animals could be exposed to sheen hydrocarbons in the water draining down the beach. At most, intertidal organisms will be exposed to oil sheens emanating from the shore for a brief time (about 10 to 15 minutes) twice during each tidal cycle when the organisms emerge during the falling tide and submerge during the rising tide, if sheens are actually present at these times. Under such an exposure regime, relatively high concentrations of hydrocarbons in the sheens would be required to produce acute or chronic biological effects.

The composition and relative concentrations of hydrocarbons in crude oil sheens will depend on the composition and, therefore, the degree of weathering of the oil from which the sheen emanated. It can be predicted that as the crude oil weathers and becomes depleted of the more soluble lower molecular weight hydrocarbons, the sheens derived from the oil also will become depleted of lower molecular weight hydrocarbons relative to higher molecular weight hydrocarbons. This appears to be the case. Sheens collected in April and October, 1989, from the Bay of Isles have different compositions relative to unweathered North Slope crude oil (Figure II-7). Both sheens are depleted of naphthalenes and to a lesser extent of other low molecular weight aromatics relative to the unweathered crude oil. However, the October sample is slightly more depleted than the April sample, indicating greater weathering.

Because the sheens from weathered crude oil are depleted of the more toxic fractions of the oil (the naphthalenes, phenanthrenes, and dibenzothiophenes: Neff and Anderson, 1981), they can be expected to be less toxic than the fresh crude oil or sheens derived from it. The available scientific literature indicates that weathered crude oil, and by inference sheens and water-soluble fractions produced from it, are substantially less toxic than the fresh crude oil (Guillen and Palafox, 1985; Capuzzo, 1987).

As shown in the previous section, there have been decreases in the frequency and volume of oil in sheens. Thus, the effects of subsurface oil released from the beaches likely will be of little or no consequence to marine birds or mammals if (Exxon's data are correct), a conclusion supported by the lack of any reports in 1990 of oiled birds or marine mammals in Prince William Sound.

Figure II-11 shows zones of convergence as depicted by ADEC. Concern has been expressed that sheens could congregate in convergence

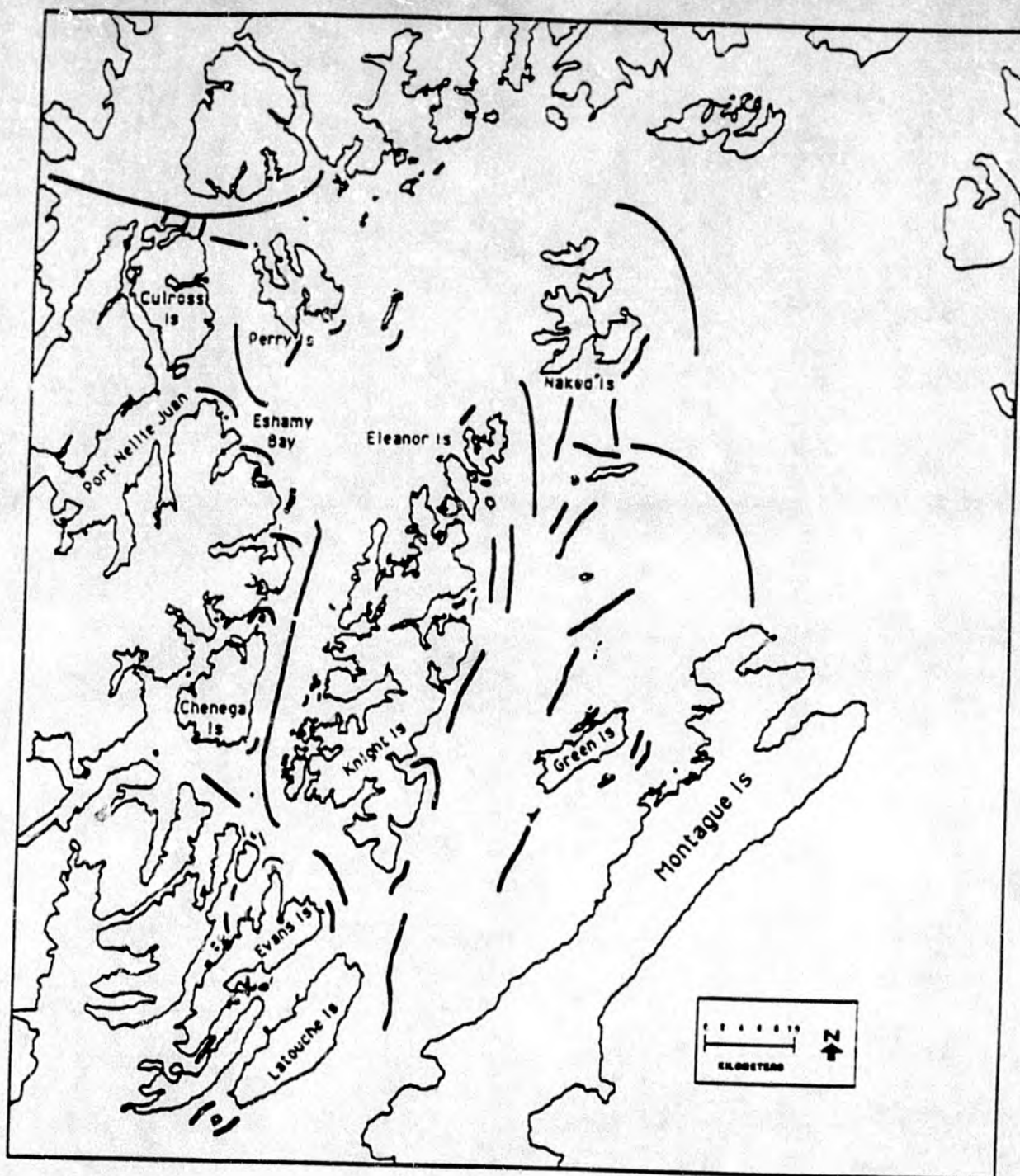


Figure II-11. Zones of convergence in Prince William Sound.

zones and remain there for a length of time, increasing the potential for impacts to birds that also concentrate to feed in these zones. In June 1989, NOAA studied the potential for oiled popweed to impact the Northern Prince William Sound fishery district. Because a relatively rare storm could transport popweed (which had been exposed to heavily oiled beaches) to vulnerable areas, it was recommended that sampling be continued through that fishing season. It was also estimated that the residence time for fresh oil in convergence zones may be from 2 to 10 days.

Effects on Fisheries

The potential effects of sheens on fishery species will depend on the amount, persistence, and composition of the sheen and the mechanism of exposure of fishery species to the sheen. As discussed above, Exxon's data indicate that sheens in Prince William Sound typically are small, often containing no more than a few liters of oil, and are patchy in distribution. They usually are short-lived. Oil sheens dissipate rapidly due to natural weathering processes, including physical dispersion into the water column by breaking waves or downwelling in tidal rips (Word et al., 1986), evaporation (Stiver et al., 1989), degradation by the abundant bacteria living at the sea surface (Rambeloarisoa et al., 1984), and photooxidation by sunlight (Barth, 1984).

A great many species of organisms live on or just below the surface of the ocean. Neuston are bacteria, plants, and animals that spend all or part of their life cycles associated with the water surface (Hardy, 1990). Included among the neuston are the eggs and larvae of several species of fish and invertebrates that spend the remainder of their lives deep in the water column or on the bottom of the sea. Animals that produce highly buoyant eggs and larvae may suffer some losses if exposed to surface sheens. Research conducted in Puget Sound has shown the relatively high potential for effects in buoyant eggs exposed to sea surface microlayers. These microlayers had high concentrations of many pollutants, including aromatic hydrocarbons. The same effects could be expected in Prince William Sound where surface sheens exist. However, the magnitude of these effects would be small.

Walleye pollock and several species of soles are examples of commercially important Alaskan species of fish whose eggs and early

larvae are neustonic. In sheens from Puget Sound, Washington, there was a poor correlation between concentrations of aromatic hydrocarbons in surface sheens and survival of the neustonic eggs of sand sole (Hardy et al., 1987a,b). For example, 36 percent of the fish eggs exposed to a sheen containing 8,030 ppb of total PAHs (as well as high concentrations of PCBs, pesticides, and metals) produced normal larvae. By comparison, all sheen samples from Prince William Sound analyzed to date contained 30 ppb or less of total PAHs (Neff, 1990). Some neustonic organisms seem to be able to adapt to sheens containing high concentrations of PAHs, primarily from combustion sources (Riznyk et al., 1987). Thus, based on these studies, it seems highly unlikely that sheens of weathered crude oil emanating from subsurface deposits of oil on shorelines will be toxic or produce harmful effects in plants and animals, including eggs of some fishery species, living in the neuston.

Pacific herring spawn in nearshore waters of Prince William Sound and deposit their eggs on intertidal and shallow subtidal stands of brown macroalgae. The eggs deposited on intertidal kelp could be exposed intermittently to oil sheens during successive tidal cycles. If droplets of fresh oil come in contact with and adsorb to the eggs, the eggs usually die or the embryos are malformed. However, a sheen of weathered crude oil is much less sticky than fresh crude oil or a recently-formed mousse and probably would not stick in biologically significant quantities to the eggs. In addition, the sheens are depleted of the more toxic fractions of the oil and so would be much less toxic to the eggs than fresh oil. Pearson et al. (1985) showed that herring eggs were not particularly sensitive to dispersed Prudhoe Bay crude oil. Exposure of the eggs to about 2,000 ppb of the dispersed oil for four days had no effect on the percent of eggs that hatched, the time to hatch, or on larval abnormalities. Thus, it is unlikely that the traces of toxic petroleum hydrocarbons in sheens of weathered crude oil would have significant deleterious effects on intertidal and shallow subtidal herring eggs.

The next spawn of Pacific herring in Prince William Sound will be in about 10 months. By that time the frequency of North Slope crude oil sheens on the water surface in areas where herring spawn should be substantially lower than the frequency observed in 1990, decreasing the likelihood that eggs will be exposed to crude oil sheens.

Adults of commercially important fishery species in Prince William Sound do not feed at the water surface and are unlikely to come in direct contact with petroleum hydrocarbons in surface sheens. In addition, adult fish are not particularly sensitive to oil. Effects on adult fish usually are reported at concentrations of oil hydrocarbons dissolved in the water column in the range of 1,000 to 50,000 ppb, whereas growth of young fry of some species of salmon was affected by oil concentrations in the range of 700 to 5,000 ppb (Vandermeulen and Capuzzo, 1983). The acutely lethal concentration of the water soluble fraction of Cook Inlet crude oil for pink salmon fry was about 1700 ppb (Rice et al., 1979). Sublethal effects on eggs and larvae of a few species of fish during chronic exposure to aromatic hydrocarbon concentrations of about 10 ppb were reported by Capuzzo (1987). Coho salmon were able to home successfully in seawater after exposure to 700 ppb of chemically dispersed Prudhoe Bay crude oil (Nakatani et al., 1985). Continuous exposure for 14 days of Pacific herring larvae to 300 ppb of Cook Inlet crude oil produced a significant decrease in growth rate (Carls, 1987). Ingestion of food containing 6,000 ppb oil had no effect on the larvae.

Concentrations of potentially toxic petroleum hydrocarbons measured in or directly under sheens of weathered North Slope crude oil are many times lower than concentrations required to cause acute lethal or chronic sublethal effects in juvenile and adult fish of commercial importance. Therefore, it is unlikely that the sheens coming from shores with subsurface oil deposits will cause observable harm to commercial fishery species.

There is also some concern that oil sheens could contaminate fishing nets and other fishing gear, and so taint the catch. This is unlikely. As discussed above, the amount of hydrocarbons in an oil sheen is very small per unit area of the sea surface. Therefore, the amount of contact between the sheen and a net hauled through a sheen would be very small. The sheen oil is not as sticky as fresh oil and so very little of the oil would stick to the water-wet net material. Fish coming in contact with a net that had been exposed to a sheen also would not be likely to retain much oil on their surface. Actual tainting of edible fish flesh requires that the living fish accumulate hydrocarbons from the water column or from its food. However, if surface contamination of fish from contact with tar balls or

mousse was heavy, the flesh could become tainted during processing of the catch.

The Alaska Department of Fish and Game (ADF&G) has a policy of closing fishing areas if oil sheens are sighted in the area. This policy is designed to assure consumers that Alaskan seafood is uncontaminated. Thus, as a result of this policy, sheens do have a negative effect on small segments of selected fisheries, even if the sheens do not affect the fishery species themselves. As discussed above, sheens originating from deposits of subsurface weathered crude oil appear to be decreasing and are not likely to be significant in future years. Sheens are surely to be generated during excavating and they are not likely to be controlled all of the time. Therefore, if the subsurface oil deposits were left in place to weather naturally or to be treated by other methods, it is unlikely that there would be any difference in the impact on fisheries due to local closures caused by sheens in 1990.

II.A.5 HUMAN USE CONSIDERATIONS UNDER CONTINUED NATURAL CLEANSING AND APPROVED 1990 TREATMENTS

Human uses such as recreation, subsistence uses, and commercial fishing would most likely be negatively affected by remaining subsurface oil. The 1990 approved treatments that include such things as storm berm relocation and bioremediation will eliminate most of the existing living organisms in the treated beach sediments and leave remaining subsurface oil below the effective working depth of these treatments. Sheening of oil from the sediments would displace nearshore commercial fishing by gillnetters and seiners. Sheening is sufficient basis for closure of the fishery in the local area. The duration of this displacement would depend on the persistence of sheening. Recreation would be impaired whenever remaining oil is encountered by the recreationist. Bleeding of oil from the sediments, exposure of subsurface oil due to natural changes in the beach geomorphology or contact with subsurface oil in locations where they are likely to dig into the beach for the purpose of building a campfire, clam digging, or other recreational activity are likely situations that would contaminate recreational users and their equipment. Subsistence activities, especially those associated with the gathering of subsistence food

from the intertidal area would continue to be curtailed due to the presence of oil. The slowed recolonization of intertidal biota and the risk of oil contact likely be reduced if sheening persists in the area.

Other activities associated with subsistence uses of these shorelines such as hunting, camping or fish drying would be negatively affected in the same manner as the recreation user if the subsistence user encounters oil.

II.A.6 ULTIMATE DISPOSITION OF SUBSURFACE OIL

Dispersion

When an oil/water mixture is subjected to turbulent mixing or wave action, droplets of oil break away from the main mass of the bulk oil and become suspended or dispersed in the water phase as small droplets. Because of the high surface tension at the oil/water interface, the droplets tend to coalesce to form larger droplets that return rapidly to the bulk oil phase. If natural or man-made surfactants are present, the surface tension is reduced and small droplets can form a relatively stable emulsion in the water phase. Subsurface oil in contact with pore water can be dispersed by normal tidal flushing if water movement and turbulence are great enough. However, as oil weathers, its viscosity increases, decreasing the tendency, and increasing the energy required, to form oil-in-water dispersions. On the other hand, some weathering processes result in the production of polar by-products of petroleum hydrocarbons, some of which have surfactant properties. In addition, many hydrocarbon-degrading bacteria produce surfactants that increase the surface area of the oil, enabling the bacteria to better metabolize it. These endogenous and biological surfactants may aid in dispersing the bulk oil into the pore water, especially during high energy situations, such as during storms.

Photooxidation and microbial degradation of the crude oil on the shores of Prince William Sound have produced polar degradation products that tend to remain with the oil. Many of the polar compounds are in the resin/asphaltene fractions of the oil and are not well characterized. However, analysis of samples of weathered North Slope crude oil from Prince William Sound by X-ray photo-electron microscopy has shown that carboxylic acids have been produced during weathering of the oil.

The relative concentrations of polar degradation products of hydrocarbons in the oil on shorelines increase as weathering of the oil occurs, indicating that the polar compounds are not readily leached from the bulk oil. Concentrations of polar organic compounds in oil samples collected on the shores of Prince William Sound have increased between March 1989 and January 1990 (Figure II-9). The increase was slow from March to June. From June to October, the concentration of polar compounds in the oil rose from about 7% to about 20% by weight of the residual oil. In the fall, the rate of increase in the concentration of polar compounds decreased again. The rate of polar organic compound production follows annual trends of intensity of solar radiation and water temperature.

These polar compounds are important because they increase the ease with which the residual oil can be dispersed into the water column by natural cleansing or human water-washing of the shore. They also have a profound influence on the interaction of the oil and the surfaces of rocks and finer sediment particles, particularly clays. The polar functional groups bind more strongly with rock or fine-particle surfaces than nonpolar functional groups do. This interaction is particularly important in the formation of flocs of oil droplets and clay particles which are removed easily from the shore by normal tidal pumping (see following section).

Flocculation

The constant movement of ice in glaciers grinds up the underlying rock to produce a fine-grained mineral dust, sometimes called glacial flour. Glacial flour is composed of micron-sized plate-like or angular mineral particles. This material is an important natural ingredient of the fine-grained marine sediments of Prince William Sound. It is an important component of the fine-grained sediment phase on many of the coarse-grained shorelines in Prince William Sound.

Research performed by Exxon has shown that these glacial flour particles interact in seawater with oil droplets to form a solids-stabilized emulsion that adheres less strongly to rocks than the bulk oil. The emulsion has the appearance under the microscope of a fluffy flocculate. It is formed when polar components in the oil residue are attracted to the electrically-charged surfaces of fine mineral particles such as clays,

quartz, and silt in the presence of salt water. The process of oil flocculation will be discussed only briefly here in relation to the possible fate and effects of subsurface oil deposits on shorelines of Prince William Sound. A full report on these processes has been published (Bragg et al., 1990).

The emulsions or flocs form naturally wherever seawater, weathered oil containing high concentrations of polar substituents, and glacial flour occur together, as in subsurface deposits of oily sediments in the intertidal zone of shores in the Sound. The emulsions have a complicated and variable structure. In general, they consist of aggregates of many micron-sized droplets of weathered oil coated with mineral fines and surrounded by seawater. Flocculated clays provide the basic framework of the emulsions by weakly binding the oil droplets together. The aggregates have dimensions of from about 1 μm to about 100 μm in diameter, depending on the oil composition, mineralogy of the solid fines, amount of water agitation, and the relative concentrations of mineral fines, oil, and seawater.

The individual aggregates of the flocs are easy to wash from the rock surface because the polar bonding sites at the oil/water interface have been coated with the small mineral fines, and this reduces the ability of the oil to adhere to the larger gravel substrate. The components in the oil that cause it to stick to the gravel are polar functional groups, such as those containing hetero-atoms (N, S, O), in the high molecular weight asphaltene fraction of the oil. As discussed above, as the oil weathers, additional polar groups, particularly carboxylic acids, are produced by photooxidation and bacterial degradation. These contribute to the stickiness of the residual oil, but also contribute to stabilization of the oil/particle/seawater emulsions. As the oil becomes more polar with time, additional mineral fines bond to these polar sites, permitting the residue oil to remain as an emulsion accessible to additional weathering processes such as leaching and biodegradation, rather than becoming a more viscous asphalt-like solid on rocks, resistant to further degradation.

The emulsion also exhibits a fairly large hydrodynamic drag in flowing water because of its large surface area per unit weight. Thus, it is more easily swept away by fairly slow water currents. For example, in a series of column tests with 88 kg of oily gravel from Smith Island, almost three-fourths of the oil was removed from the gravel in less than 24 hours

by flowing seawater through the column at velocities up to 19 ft/min (3.8 cm/sec), just sufficient to cause the gravel in the column to move slowly. This velocity is at least an order of magnitude less than water velocities imparted by gentle waves on the beach surface, and possibly another order of magnitude less than would be observed on the surface of high-energy beaches during a storm.

In contrast, the rate of movement of water through the interstitial spaces of intertidal sediments during normal tidal flushing is quite low. If the rate of tidal flushing of subsurface sediments is 10 pore volumes/tidal cycle, the rate of lateral movement of water through the pore spaces will be in the range of 0.05 to 0.1 cm/sec, depending on sediment porosity. In the column experiments, the minimum flow velocity required to dislodge flocs from rock surfaces is about 0.6 cm/sec. Thus, relatively little floc material is likely to be dislodged during normal tidal flushing. However, rapid and massive export of oil flocs from subtidal sediments probably will occur during storms severe enough to move sediments about.

The density of the flocculated emulsion is comparable to that of seawater. Most of the floc particles are lighter than seawater and will float on the water surface and be widely distributed by winds, waves, and currents after removal from the beach, especially since they are most likely to be removed from the substrate during storms. For those floc particles that do settle, sinking rates were estimated to be less than 1 ft/day (1.4×10^{-4} cm/sec) for particles with diameters of 1 to 10 μm and up to 45 ft/day (6×10^{-3} cm/sec) for the largest, heaviest flocs. At these settling rates, the oil/particle/seawater emulsions will be dispersed widely and diluted to very low concentrations before settling to the bottom. During settling, bacteria will continue to degrade the hydrocarbons in the flocs, further decreasing the amount of hydrocarbons reaching the bottom.

Flocs composed of weathered oil droplets and mineral particles will be much less toxic than the weathered oil in solution and probably less toxic than droplets of weathered oil, because the presence of a surface layer of mineral particles on the droplets will inhibit transfer of hydrocarbons from the droplets to organisms that might come in contact with floc particles. Because of their low toxicity and rapid dilution in the ocean, oil flocs will not be harmful to living plants and animals in Prince William Sound.

The formation of stable emulsions with clay-sized particles may help explain how some of the oil was removed naturally from the shores of Prince William Sound during the winter. It also suggests that the hydrocarbons washed from the shore were not merely redeposited at measurable concentrations in shallow subtidal waters near the shore where they might have the most adverse biological effects. Instead, they were possibly carried away and diluted and degraded to unmeasurable concentrations. This form of mobilization of subsurface oil will continue to go on wherever deposits of subsurface oil and glacial flour coexist, assuming those results from the laboratory are duplicated in the field. The rate of floc formation may increase as the oil continues to weather and the concentration in the oil of polar functional groups continues to increase.

Subtidal Deposition

Introduction. A team of ADEC divers visited each of the two rock washing candidate sites. On 7 June 1990, the team visited Sleepy Bay, Latouche Island, and on 8 June, Point Helen, Knight Island. The team constructed topographic profiles at each site and made substrate and biological observations along them. NOAA transect N-18 was continued offshore in Sleepy Bay, and NOAA transect N-1 was continued offshore at Point Helen. Subtidal profiles are presented in Figure II-12. Subtidal sediment samples were collected and released for analysis by NOAA.

Point Helen (KN-405: N-1). Table II-5 presents subtidal observations at site N-1. Changes in substrate occur where noted in the table, otherwise they remained the same to the next reported depth. In general, the substrate graded from a boulder, cobble, and sand mix at a few meters depth, to rocky gravel at greater depths, and to sandy silt at 100m. Below the mean lower low water (MLLW) level to 60m out, a dense kelp "forest," which was thick enough to make sampling of sediments difficult, covered a boulder/cobble substrate. The boulders had a coat of encrusting coralline algae and some tube worms. At approximately 60m from the MLLW mark, the kelp abruptly gave way to a predominantly sand bottom that graded abruptly to a greater proportion of fines at 100m. This bottom showed evidence of burrowing, and sea stars (*Pycnopodia*) were present as widely scattered individuals. Samples were collected at 0, 5, 10, 25, 50, and 100m water depths.

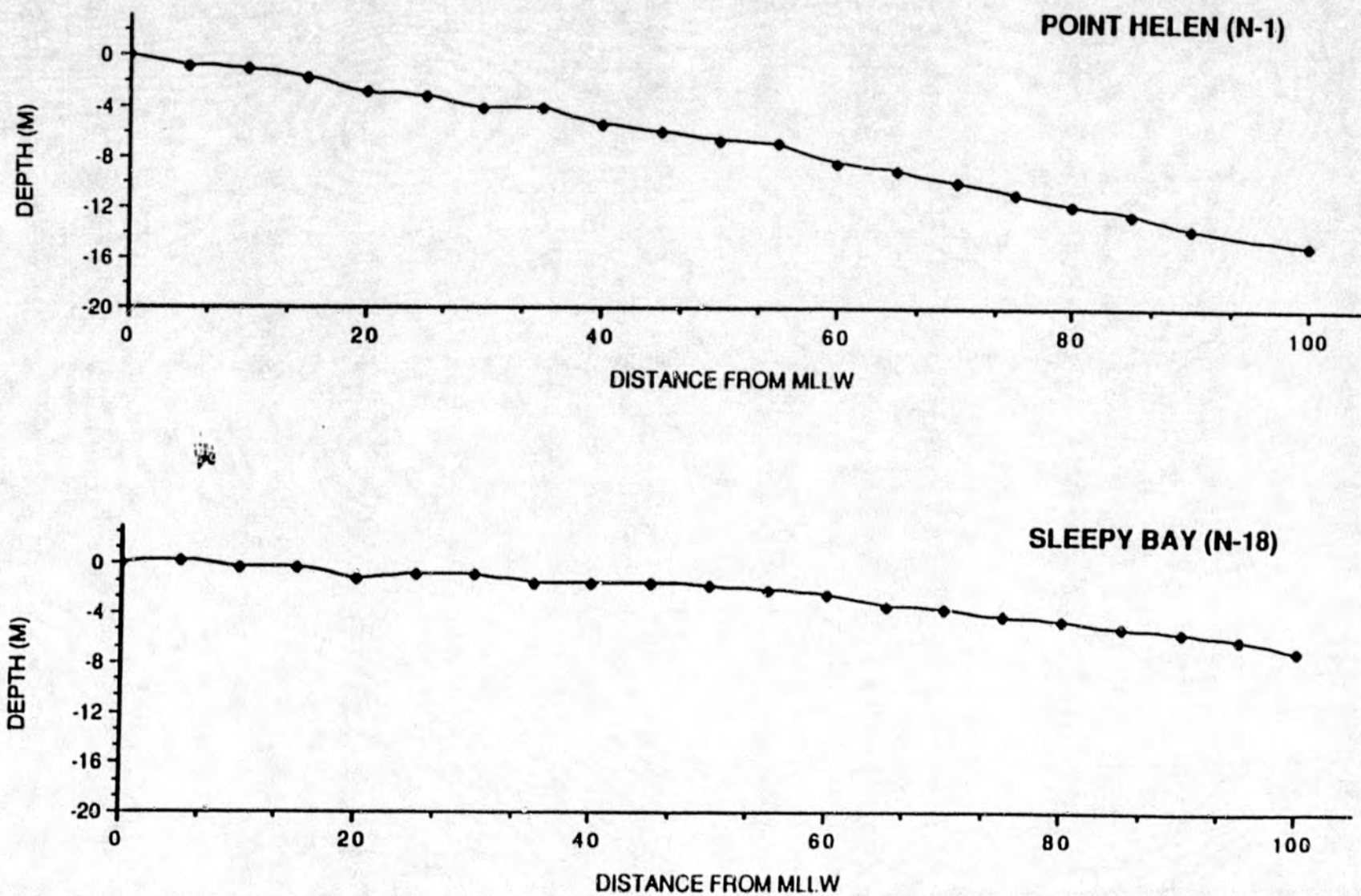


Figure II-12. Subtidal profiles off NOAA stations N-1 (upper) and N-18 (lower) in June 1990.

Table II-5

Point Helen (N-1): Dive occurred between 1616 and 1654 on 8 June 1990. Tidal height at start of dive was +8 feet. Start of 100-meter subtidal transect began at 8 fsw.

<u>Distance From MLLW</u>	<u>Observations</u>
0 meters	boulder armor with cobbles below; <i>Ulva</i> present in patches
5 meters	boulders continue, <i>Alaria</i> more common
10-15 meters	<i>Alaria</i> , 100% coverage
20 meters	laminarians begin to replace <i>Alaria</i> , some hedophyllum present, over boulders
25 meters (3 photos)	laminarians, hedophyllum, some encrusting algae on boulders
30-35 meters	less boulders, more gravel
40 meters	sand/gravel/few boulders, hedophyllum, some <i>Pycnopodia</i>
50 meters	<i>Laminaria</i> , hedophyllum, evastarias on sand/gravel substrate
55 meters	80% sand, 80% hedophyllum
60 meters	80% sand, 20% gravel, algae ends abruptly
65 meters	same substrate with diatom scum
70 meters	same substrate with shell fragments
75 meters	90% sand, some gravel, hedophyllum on large cobbles
80 meters	70% sand, 15% silt, some gravels, shell fragments
85 meters	scattered red algae, substrate grading to more fines
90 meters	more fines (fin kicks begin to resuspend silts)
100 meters	same substrate, grading to approx. 40% silt

Sleepy Bay (LA-18: N-18). Table II-6 presents subtidal observations at site N-18. Offshore, shallow depths were dominated by bedrock outcrops with sand and silt pockets; with increasing depth, outcrops diminished and silt began to dominate the bottom. In general, the subtidal community was composed of dense large brown kelps. Kelp leaves had thin white patches where spores had been released, and a light covering of spirorbid worms. White flocculent, probably organic in origin, covered much of the area from mid-transect to the end. Samples were collected at 0, 10, 25, 50, and 100m water depths.

Chemical Results of Sediment Samples. Results of chemical analysis by GC/MS of the subtidal samples collected at Sleepy Bay and Point Helen are shown in Table II-7. Extreme care in the analysis of these samples was taken because of the large fraction of biogenic hydrocarbons and their interferences. These results indicate that the level of PAH contamination is very low. Of the six samples analyzed from Point Helen, the total PAHs ranged from 0.1-8.8 ppb. At Sleepy Bay, the values ranged from 2.0 to 130 ppb. The general characteristics of the subtidal oil appear to be moderate to heavily weathered.

Higher concentrations would be expected in the more sheltered setting off Sleepy Bay. Since there does not appear to have been large-scale depositions of oiled sediments in the nearshore subtidal zone over the 1989-90 winter, when shoreline oil concentrations were high, future deposition of oiled sediments from remaining subsurface oil should be minimal.

Environmental Impacts

As described above in Sections I.C.4 and II.A.4, petroleum hydrocarbons will be washed continuously at a slow rate from deposits of subsurface oil in the intertidal zone by tidal pumping and freshwater runoff. In addition, if the subsurface sediments where the oil resides are aerobic, biodegradation by marine hydrocarbon-degrading bacteria will contribute to a decrease over time in the amount of subsurface oil remaining on the shore.

Biodegradation is the ultimate fate of all oil that is not removed from Prince William Sound by human activities, evaporation, and photooxidation. Atlas and Bronner (1981) estimated that the biodegradation The rate of rate of petroleum from the AMOCO CADIZ oil spill in intertidal

Table II-6

Sleepy Bay (N-18): The dive occurred between 2001 and 2045 on 7 June 1990. Tidal height at start of dive was approximately +4.0 feet. Start of 100 meter subtidal transect thus began at 4.0 fsw.

<u>(Distance From MLLW)</u>	<u>(Observations)</u>
0-20 meters	60% cobble, 40% pebble, w/barnacles (<i>B. glandula</i>) actively feeding (approx. 15% coverage on larger cobbles)
20 meters	light flocculent, algal growth on cobbles, <i>Pycnopodia helianthoides</i> individual present
25 meters	<i>Alaria</i> (20% coverage)
30 meters	<i>Alaria</i> and hydroids
35 meters	dense <i>Laminaria</i> begins, fully covering cobbles
45 meters	<i>Laminaria</i> continues, with white (organic) flocculent on blades
50 meters	tube worms (<i>Serpula</i> or <i>Crucigera</i>) present on larger cobbles under brown algae
55-70 meters	large cobbles continue under dense brown algal cover
70 meters	encrusting coralline algae on cobbles, spirorbids common on <i>Laminaria</i> blades
80 meters	substrate shifting to sand/cobble mix
90 meters	sand/gravel/pebble under <i>Laminaria</i> one starfish found w/tumor or undeveloped arm (bump where arm should radiate out)
100 meters	80% sand with a few boulders and silt

Table II-7. Concentration of Specific Compounds in Subtidal Sediments at the Candidate Beaches.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	Pt.Helen	Pt.Helen	Pt.Helen	Pt.Helen	Pt.Helen
SAMPLE STATION	N1	N1	N1	N1	N1
DISTANCE FROM SHORE	0M	5M	10M	25M	50M
SAMPLE TYPE	grav.	peb.	peb.	sed.	sed.
MONTH SAMPLED:	6/8/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)
NAPHTHALENE	ND	ND	ND	ND	ND
C-1 NAPHTHALENE	ND	ND	ND	ND	0.022
C-2 NAPHTHALENE	ND	ND	ND	0.043	0.330
C-3 NAPHTHALENE	ND	ND	ND	0.022	0.087
C-4 NAPHTHALENE	ND	ND	ND	0.024	0.110
FLUORENE	ND	ND	ND	ND	0.006
C-1 FLUORENE	ND	ND	ND	0.019	0.019
C-2 FLUORENE	ND	ND	ND	0.017	0.064
C-3 FLUORENE	ND	ND	ND	0.027	0.120
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND	ND	2.200
C-2 DIBENZOTHIOPHENE	ND	ND	ND	0.036	0.240
C-3 DIBENZOTHIOPHENE	ND	ND	ND	0.120	0.810
PHENANTHRENE	ND	ND	ND	0.017	0.022
C-1 PHENANTHRENE	ND	ND	ND	ND	0.018
C-2 PHENANTHRENE	ND	ND	ND	0.022	0.130
C-3 PHENANTHRENE	ND	ND	ND	0.045	0.780
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	0.066
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.024	0.330
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.034	0.520
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.100	0.440
FLUORANTHRENE	ND	ND	ND	ND	0.011
PYRENE	ND	ND	ND	ND	0.013
C-1 PYRENE	ND	ND	ND	ND	0.081
C-2 PYRENE	ND	ND	ND	0.024	2.100
BENZO(a)ANTHRACENE	ND	ND	ND	ND	0.008
CHRYSENE	ND	ND	ND	0.009	ND
C-1 CHRYSENE	ND	ND	ND	0.014	0.160
BENZO(b)FLUORANTHRENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	0.041
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYRENE	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHRACENE	ND	ND	ND	ND	ND
BENZO(g,h,i)PERYLENE	ND	ND	ND	ND	0.014
TOTAL=	ND	ND	ND	0.60	8.70

est. det. limit 0.01 ng/mg

All values are valid to 2 significant figures only.

Table II-7. Cont.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	Pt.Helen	Sleepy B.	Sleepy B.	Sleepy B.	Sleepy B.
SAMPLE STATION	N1	N18	N18	N18	N18
DISTANCE FROM SHORE	100M	0M	5M	10M	25M
SAMPLE TYPE	sed.	peb.	peb.	sed./grav.	peb.
MONTH SAMPLED:	6/8/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/mg)	(ng/g)	(ng/g)	(ng/g)	(ng/g)
NAPHTHALENE	0.010	0.002	0.010	0.039	0.002
C-1 NAPHTHALENE	0.016	0.004	0.033	0.044	0.003
C-2 NAPHTHALENE	0.270	0.027	0.400	0.280	0.021
C-3 NAPHTHALENE	0.068	0.052	0.035	0.600	0.016
C-4 NAPHTHALENE	0.022	0.089	0.120	1.400	0.012
FLUORENE	0.005	0.002	0.023	ND	ND
C-1 FLUORENE	0.012	0.020	0.030	0.180	0.056
C-2 FLUORENE	0.019	0.200	0.190	1.600	0.049
C-3 FLUORENE	0.130	0.820	0.800	0.570	0.120
DIBENZOTHIOPHENE	0.003	0.007	0.017	0.034	0.004
C-1 DIBENZOTHIOPH.	0.840	0.096	1.300	0.890	0.035
C-2 DIBENZOTHIOPH.	0.097	0.007	1.100	10.000	0.170
C-3 DIBENZOTHIOPH.	0.310	4.500	4.100	30.000	0.190
PHENANTHRENE	0.110	0.013	0.210	0.120	0.009
C-1 PHENANTHRENE	0.023	0.072	0.110	0.550	0.025
C-2 PHENANTHRENE	0.072	0.860	0.800	6.000	0.120
C-3 PHENANTHRENE	0.210	3.400	0.230	15.000	0.210
NAPHTHOBENZOTHIOPH.	0.008	0.150	0.180	2.300	0.012
C-1 NAPHTHOBENZOTHIOPH.	0.094	3.300	2.800	13.000	0.200
C-2 NAPHTHOBENZOTHIOPH.	0.170	5.100	4.700	17.000	0.440
C-3 NAPHTHOBENZOTHIOPH.	0.340	4.600	4.200	12.000	0.650
FLUORANTHRENE	0.023	0.000	0.320	0.037	ND
PYRENE	0.024	0.062	0.260	0.021	0.014
C-1 PYRENE	0.052	0.450	0.580	2.400	0.080
C-2 PYRENE	0.110	1.300	1.200	5.700	0.230
BENZO(a)ANTHRACENE	0.007	0.002	0.160	ND	0.014
CHRYSENE	0.060	0.018	1.400	0.210	0.140
C-1 CHRYSENE	0.080	1.300	2.200	7.400	0.240
BENZO(b)FLUORANTHRENE	0.014	0.011	0.380	0.032	0.054
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	0.016	0.016	1.100	0.087	0.100
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	0.002	0.058	ND	0.014
DIBENZO(a,h)ANTHR.	ND	0.010	1.200	ND	0.013
BENZO(g,h,i)PERY.	0.008	0.004	0.310	ND	0.034
TOTAL=	3.20	27.00	31.00	130.00	3.30

est. det. limit 0.01 ng/mg

Table II-7. Cont.

GC/MS QUANT RESULTS		
SAMPLE LOCATION	Sleepy B.	Sleepy B.
SAMPLE STATION	N18	N18
DISTANCE FROM SHORE	50M	100M
SAMPLE TYPE	peb./shell	peb./shell
MONTH SAMPLED:	6/8/90	6/8/90
COMPOUND	(ng/g)	(ng/g)
NAPHTHALENE	ND	0.012
C-1 NAPHTHALENE	ND	0.028
C-2 NAPHTHALENE	0.028	0.310
C-3 NAPHTHALENE	0.011	0.200
C-4 NAPHTHALENE	0.086	0.850
FLUORENE	ND	0.016
C-1 FLUORENE	ND	0.096
C-2 FLUORENE	0.027	0.820
C-3 FLUORENE	0.072	2.700
DIBENZOTHIOPHENE	0.001	0.018
C-1 DIBENZOTHIOPHENE	0.016	1.200
C-2 DIBENZOTHIOPHENE	0.049	4.900
C-3 DIBENZOTHIOPHENE	0.080	0.840
PHENANTHRENE	0.007	0.055
C-1 PHENANTHRENE	0.013	0.330
C-2 PHENANTHRENE	0.073	3.600
C-3 PHENANTHRENE	0.200	6.700
NAPHTHOBENZOTHIOPHENE	0.009	0.035
C-1 NAPHTHOBENZOTHIOPHENE	0.190	5.200
C-2 NAPHTHOBENZOTHIOPHENE	0.430	8.100
C-3 NAPHTHOBENZOTHIOPHENE	0.480	6.700
FLUORANTHRENE	0.009	0.028
PYRENE	0.010	0.025
C-1 PYRENE	0.044	1.100
C-2 PYRENE	0.110	2.400
BENZO(a)ANTHRACENE	ND	ND
CHRYSENE	0.064	0.110
C-1 CHRYSENE	0.120	3.700
BENZO(b)FLUORANTHRENE	0.013	0.480
BENZO(e)PYRENE	ND	ND
BENZO(a)PYRENE	0.008	1.300
PERYLENE	ND	ND
INDENO(1,2,3-cd)PYRENE	ND	0.075
DIBENZO(a,h)ANTHRACENE	0.012	ND
BENZO(g,h,i)PERYLENE	0.005	0.310
TOTAL=	2.10	52.00

est. det. limit 0.01 ng/mg

sediments was 0.5 μg hydrocarbons/gram dry sediment (parts per million) per day. The rate of microbial degradation of hydrocarbons in anaerobic sediments was several orders of magnitude lower than in aerobic sediments (Atlas et al., 1981). Shiaris (1989a,b) reported that both naphthalene and phenanthrene are degraded in sediments of Boston Harbor, Massachusetts at a rate of about 0.4 μg /gram dry sediment/day. The rate of degradation of the PAHs increased as the concentration of the PAHs in the sediment increased. The rate of microbial degradation of oil in sediments usually is nutrient-limited, so if bioremediation of subsurface oil deposits is performed, degradation rates can be expected to be much higher.

Any oil that washes from the sediments onto the water surface as a sheen or into the water column as a dispersion, flocculate, or dissolved phase, also is subject to microbial degradation. Estimated rates of microbial degradations of petroleum hydrocarbons from crude oil in the water column range from 1 to 10 μl /day beneath the surface slick produced by crude oil from the AMOCO CADIZ spill (Aminot, 1981).

The buried oil itself will have no environmental effects as long as it remains buried on the shore and out of contact with living organisms. Potential effects of sheens possibly emanating from subsurface oil deposits were discussed above. However, if some of the subsurface oily sediment is mobilized from the upper shore by winter storms, it may be deposited in a location where living plants and animals might come in contact with it.

The oil coming off a shore during a storm probably will be associated primarily with clay flocs. These flocs are buoyant or neutrally buoyant and so will be carried away with the prevailing storm currents and be diluted over a wide area. The oil in the flocs, because of its stable association with clay-sized particles, probably is much less bioavailable than physically dispersed oil droplets. This low bioavailability coupled with the expected rapid dilution of the flocs in the water column will yield subsurface oil of minimal toxicity to organisms living in the water column.

Some of the oil coming off the shore may be associated with high concentrations of suspended particles (silt and sand from the shore) and be deposited with them in subtidal sediments. Studies of the Baffin Island experimental oil spill (Boehm et al., 1987) and the AMOCO CADIZ oil spill (Gundlach et al., 1983) have shown that in the few months immediately

after a spill, concentrations in excess of 100 ppm of oil can be deposited in subtidal sediments if oil comes ashore and subsequently erodes from the beach. Because of substantial dilution and dispersion of the oil during remobilization and redeposition, the concentrations in subtidal sediments of oil derived from shore erosion will usually be much less than the concentrations of oil buried in the intertidal zone.

Oil bound to sediments is much less toxic than oil in solution or dispersion in the water column. This is because the sediment-bound oil has only a very limited bioavailability to marine organisms associated with the sediment (Neff, 1984). Anderson et al. (1978) exposed trays containing sediments contaminated with 700 to 6,000 ppm of Prudhoe Bay crude oil in the intertidal zone of Puget Sound. Concentrations of hydrocarbons in the sediments decreased by 21 to 85 percent in 100 days, depending on sediment grain size. Hydrocarbons were lost most rapidly from coarse sediments. No substantial inhibition of recruitment of benthic organisms was observed at these concentrations of petroleum hydrocarbons in sediments.

The discussion in Section II.A.3 summarized the PAH concentrations in fine-grained sediments which resulted in adverse impacts to benthic communities. The concentrations of PAH in subtidal sediments collected offshore Point Helen and Sleepy Bay are all below these levels of concern. With a much lower and decreasing source of oil-contaminated fines, it is unlikely that there will be any effects of weathered petroleum eroding from beaches on shallow subtidal benthic communities off oiled shorelines.

These studies show that oil, particularly weathered crude oil, in sediments is not very toxic to benthic marine organisms. Concentrations of petroleum hydrocarbons orders of magnitude higher than concentrations expected in nearshore sediments of Prince William Sound as a result of storm erosion of intertidal subsurface oil allow recruitment and normal development of benthic communities.

II.B. EXCAVATION/ROCK WASHING

II.B.1. EFFECTS ON BEACH SUBSTRATE

Introduction

Sediment transport and remobilization on gravel beaches is a very poorly understood process. Studies such as the ones by Carr (1971), Caldwell (1981), and Hattori and Suzuki (1978) give good indications of sediment transport directions and general clues concerning the wave parameters involved. However, their data cannot be used to calculate volumetric sediment discharges or even derive specific predictions of the nature of the detailed sorting and transportation processes. Fortunately, a year's worth of fairly detailed data have been collected by Exxon, ADEC, and NOAA on beach morphological changes at the two candidate sites, which can be used in a hindcast mode to predict future changes on the two beaches. Furthermore, we can call on the professional experience of the coastal geologists representing the three principal parties (Owens/Exxon; Gundlach and Pavia/ADEC; and Hayes/NOAA), who have studied the impact of several oil spills on gravel beaches.

Beach Stability

Resorting. If we make the basic assumption that the material to be washed would be dredged from approximately the upper one-third of the beaches, replaced to that area and graded to near its original configuration after washing, we can say the following regarding resorting at the two sites:

1. Point Helen

The present sorting is such that finer particles, namely smaller cobbles and pebbles, are sorted into berm accumulations at the top of the profile and the coarser cobbles and boulders form an armor on the middle and lower portions of the profile. We predict that if the washed material were replaced in approximately the same position it was taken from, the berms would reestablish themselves with more or less the same size grading after two or three medium-sized storms, probably in less than one year. The armoring process may require a few more storms, possibly covering a period of one to three years. Armor of gravel material was

reestablished in two years on the inner beach of Ediz Hook at Port Angeles Harbor, Washington after disruption by cleanup of the ARCO ANCHORAGE spill (Miller, 1989).

2. Sleepy Bay

NOAA's profile data indicate that sediment on the upper and lower portions of this beach is mobilized readily. Armoring is not as well developed at Sleepy Bay as it is at Point Helen. Again, the sediment resorting process on the upper profile should occur in less than one year. Because the middle portion of the beach changes more slowly, the complete reestablishment of the original profile and sediment re-sorting may require up to three years, but would probably take place sooner.

Loss of Fines. There are no significant quantities of "fines" in the sections of either beach where the oil is buried, with the sand content being less than 10% at both sites (Sleepy Bay contains up to 15% sand plus granule). After mixing of the sediment by the washing process and replacement of it on the beach, it is conceivable that some of the sand will be transported out of the beach areas. However, because the sand exists primarily as a matrix to the already fixed framework of the beach, the impact of its potential loss on the beach's morphology should be nil.

Loss of Infauna. There is very little infauna on the macrofaunal scale in the sections of the two candidate sites where oil is buried. Micro- and meiofauna that may now exist in those sections of the beaches would obviously be eliminated during the washing process.

The sediment replaced on the beach would in all likelihood be reestablished to inhabital form (for micro- and meiofauna) within a period of one to three years at both sites. This statement is based on the conclusion that the beach morphology and sediment sorting pattern would be reestablished within that time frame.

Beach Erosion. The following quote from Carter (1988) has relevance to this issue: "both residual wave asymmetry transport and overpassing abilities, plus relative immobility, favors retention of large clasts on the beach. Secondly, large coarse grained beaches, through their enhanced roughness and permeability characteristics, are more stable in higher-energy environments." Furthermore, it has been observed at numerous localities by the authors, that during storms, coarse clasts tend to move

landward, while sand moves seaward, which accounts for the omnipresent coarse-grained storm berms throughout the spill site.

The only ways we can envision serious beach erosion occurring as a result of the rock washing process follow:

- 1) The material removed is not replaced on the beach at or above MSL.
- 2) A major storm hits while the gravel is being washed, leaving the beach unprotected.
- 3) A significant amount (>30%) of fine material is present, which is carried away in suspension during the washing process.

As far as the two candidate sites are concerned, both are backed by bedrock, and both contain bedrock outcrops in the intertidal zone. Therefore, retreat of the beach of more than a few meters is virtually impossible at the two sites. Both beaches are coarse enough so that, if the washed material is replaced in the upper intertidal zone, it should stay there. In short, beach erosion (enhanced by rock washing) is not envisioned to be a significant problem at the candidate sites.

The Disruption of Armoring. Armoring is a sorting process that is best developed in the middle and lower portions of the beach profiles of Prince William Sound. Whereas the process of armor formation has been studied on gravel bars in rivers, the authors know of no such study on beaches. Armoring of a gravel beach in a wave tank experiment was recently reported by Petrov (1989), but no explanation for the process was given. On river bars, once the armor is formed, a process known as "structural strengthening" occurs, such that a stronger flow is required to transport the materials available (at least one-fourth greater).

Consequently, disruption of armoring could conceivably create a more unstable condition on the beach regarding sediment transport. However, at the two candidate sites, armoring is not as well developed in the areas where oil is buried as it is further seaward, with the Point Helen beaches showing more advanced armoring than the beaches at Sleepy Bay. Therefore, care should be taken at Point Helen to avoid disrupting the armored lower portions of the beach, if at all possible, should gravel washing be carried out.

II.B.2. EFFECTS ON INTERTIDAL BIOTA BY EXCAVATION/ROCK WASHING OF BEACH MATERIAL AND PROJECTIONS OF RECOLONIZATION

Introduction

The impacts of field implementation of the rock-washing method on indigenous biota of candidate beaches would be expected to be significant, encompassing both direct and indirect effects. The physical components of the process that will be necessary to remove the oil remaining in the targeted beach material would involve major direct effects, while the subsequent disruption of habitat would result in a number of indirect and more subtle effects primarily associated with delayed recolonization of the treated intertidal zone.

Effects of Removal/Processing/Replacement

Intertidal marine organisms generally inhabit the surfaces of beach materials such as boulders and cobbles, the depressions underneath these materials, and the interstices between these materials (see Section I.C.7). Some species live in the coarse sand and gravel that underlies the larger cobbles and boulders, generally frequenting approximately the upper 10cm of the beach materials. In order to excavate the subsurface oil remaining on the candidate beaches, the uppermost layers of surficial material must be removed, and it is likely that organisms inhabiting these strata will be displaced.

Under normal circumstances, the upper tidal zone in Prince William Sound usually supports considerably fewer species and lower numbers of organisms than the middle and lower tidal zones on the beaches (Haven, 1971). The richest intertidal communities generally inhabit the lower tidal zone (sometimes referred to as the "*laminaria* zone") that is dominated by thick algal mats and is uncovered by only minus tides. The rock-washing operations would be expected to directly affect primarily the upper portions of the intertidal beach, as these were the most heavily oiled and contain the residual amounts that would be subject to removal. However, some secondary impacts of the process would also be anticipated in the middle and lower intertidal zones.

It is very unlikely that any organisms could survive the impacts of excavation, hotwater washing, and replacement. Most of the organisms from the excavation zone would be crushed, cooked, or buried during the operation. However, it is relevant to note that the upper tidal zone, where most of the excavation work would be focused, generally does not support a very rich biotic community.

If wheeled or tracked vehicles are used on the beach to excavate the oiled material, they would affect horizons of the beach both above and below the oiled zone. Backing and turning maneuvers would crush biota outside the targeted oiled zone and rearrange substrate comprising habitat for biota. Should backing and turning maneuvers extend into the relatively rich communities of the middle and lower tidal zones, significant intertidal resources could be damaged or destroyed. These lower tidal zone resources can include large algae, prey items for salmonids and marine mammals, bivalve molluscs, and many species of nearshore fish.

Many of the prey items that juvenile salmon depend upon as they enter saltwater are detritivores, or carnivores that prey upon detritivores. The detritivores are often epibenthic zooplankton, such as gammarid amphipods and harpacticoid copepods, that live near or on the bottom and consume the debris that results from the decomposition of plant and animal matter. If the gravel washing process removes the fine particulate materials from the beach, including the detritus accumulated under boulders and cobbles, the food supply for these detritivores will be lost. Observations made at Sleepy Bay suggest that gammarid amphipods were abundant under rocks that had accumulated algal debris and absent under rocks that had no debris. The adverse impact of the removal of organic material on a key component of the nearshore food web likely would be a fairly short-term phenomenon. The detritivore-based food web could be expected to reestablish once the beach became physically stabilized within one to three years.

Dead plant and animal materials resulting from the beach treatment activities likely will be consumed by a variety of birds, crabs, or other scavengers. This sudden source of food may attract opportunistic feeders to the treatment sites, but this congregation would be expected to be a temporary phenomenon.

Recolonization of Treated Beaches

Controlling Factors. In estimating the recolonization rate and time to recovery of the beaches to be treated with the rock washer, a number of factors must be considered. First, it was assumed that the rock washer would sterilize all of the beach materials that are treated, and, therefore, recolonization would start with effectively denuded, inorganic substrate. Second, it was assumed that the recolonization process would be unimpeded by the presence of any remaining oil after treatment by rock washing. Third, it was assumed that the beaches that would be treated with rock washing are those that were both oiled and composed primarily of pebbles and cobbles.

Two important milestones that were estimated in this analysis were the time required to reach the "equilibrium point" and the time to "recovery." The equilibrium point is the time following a disturbance at which the number of species colonizing the beach has stabilized. Recovery is a variously defined concept, which in its most rigorous definition specifies the point in time at which the pre-spill conditions are attained in terms of the number of species, the relative abundance of each species, pre-spill patchiness, and the dynamic functioning of the community (i.e., the normal proportion of autotrophs, grazers, detritivores, predators). Others have adopted a less comprehensive and more pragmatic definition of recovery as being the point in time when the community in a disturbed area exhibits variation within the range of that observed in comparable communities from undisturbed control areas (Lissner et al., 1988).

The amount of information and the accuracy of the models available to estimate the recolonization equilibrium points greatly exceed those available for estimating biological recovery. Although the concept of recovery is not an overly complex one, the task of studying and estimating recovery in natural systems is extraordinarily difficult because of the number of factors considered, the inherent variability in those systems, and the lack of baseline data to which post-disturbance conditions can be compared. Ganning et al. (1984) have commented that rarely are sufficient data available to evaluate "natural" variability in a community, and they noted that a previously existing community may have been replaced by a slightly altered community that exhibits variability within a range considered "normal," despite its different composition.

In Prince William Sound, very little quantitative information is available on the intertidal communities that inhabited gravel beaches before the oil spill. While it would be possible to generate data of this type by examining unoiled beaches, such an inventory and estimates of variability within Prince William Sound gravel beach communities do not currently exist. With these limitations in mind, the operational definition of recovery that is used here is a descriptive one: that point in time when a core group of dominant species (expected in the absence of a major disturbance such as an oil spill) has returned to generally comparable levels of abundance and community structure. The core group of dominants that is expected at the candidate beaches is based upon the lists and descriptions of Rosenthal et al. (1982). This qualitative definition is necessitated by the uncertainties discussed above and the lack of information on the intertidal zone of Prince William Sound gravel beaches that would be likely candidates for the considered treatment.

The initial stages of colonization of a sterile substrate, similar to that expected after rock washing, usually begins with a bacterial and colonial diatom community (Woods Hole Oceanographic Institution, 1952; Johansen, 1971). Subsequent colonists often depend upon these organisms for food or to modify the substrate so it is suitable for further colonization. Organic matter and fine-grained material encourage the growth of the pioneer colonizing species, and because the rock washing process will remove both organic and smaller grain-size fraction materials from the beaches and not return them after treatment, it is possible that the initial stages of recolonization will be delayed. However, it should be noted that fines will be generated by sediment handling and transport back to the shore, as well as grading, replacing some of this sediment loss.

The oil that accumulated on the Prince William Sound beaches had different effects upon different species of organisms. The most resistant species survived the direct exposure to oil. However, according to data available from two locations in Herring Bay (Houghton and Erikson, unpublished), many of the organisms that initially survived the oil spill were subsequently eliminated by the effects of high temperature, high pressure beach washing. Most of the littorinid snails, green algae, brown algae, sponges, large snails and barnacles did not survive the washing. At two lower intertidal zone sites, the numbers of taxa observed before

treatment were 28 and 21 and decreased to 16 and 17 after treatment, respectively. In two upper intertidal zone sites, the numbers of taxa decreased from 14 to 5 at one site and remained unchanged at 5 taxa at the other site. In the IRISH STARDUST oil spill in Alert Bay, British Columbia, numerous resistant species of algae and invertebrates survived the effects of the oil spill (Green et al., 1974). The more sensitive amphipods did not survive, but recolonized the rock and cobble beaches within one year following the spill.

The factors that would control the recolonization rate following the selection of the rock-washing process include the time at which the beach material would be resorted and restabilized, the season during which restabilization would take place, the proximity to brood stock for potential recruitment, the size of the treated area, and the geomorphology of the post-treatment beach. The net effect of all these influences determines whether recolonization is inhibited or accelerated.

An important factor in the restabilization of the beach to pre-treatment conditions is the rate at which the layer of "armor" cobbles and rocks would be reestablished. Many of the infaunal and ambulatory species find refuge from exposure and predators under and around the relatively larger, or armoring, material or in the smaller beach material sheltered by the armoring substrate. Large cobbles (some in the form of horizontal plates) generally are uppermost on these beaches and protect the gravel underlying them. Beneath the gravel, it is common to find coarse sand, small pebbles and gravel, and, occasionally, some mud. If these materials are redistributed back onto the beach randomly after the rock washing treatment, recolonization can be seriously hampered until the materials become resorted in a manner similar to that existing before the treatment.

In the ARCO ANCHORAGE spill of 1985 in the state of Washington, Miller (1989) noted that physical disturbance of beaches from intrusive cleanup activities breached the naturally occurring armor layer, but also found that within two years much of the armor layer had been reestablished. In contrast, a recent habitat restoration project in Vancouver, B.C. (J. Marliave, personal communication; Vancouver Aquarium, 1990) returned a silted intertidal area to its status as a spawning ground for several fish species only after careful selection and placement of substrate. Other intertidal mitigation projects in the same

area that placed substrate in a more random fashion were completely unsuccessful in providing functional habitat. Although this study focused on the lower intertidal and subtidal zones, it demonstrated that in some habitats, the physical characteristics of a predisturbance beach may take a long time to naturally reestablish. Protected, low-energy beaches would probably require much longer time periods to return to their earlier configurations.

In the absence of a directed effort to redistribute cleaned substrate to approximate the physical structure of the pretreatment beach (which would obviously be a painstaking undertaking), resorting and restabilization of the beaches are expected to occur as a result of wave and tidal action. On many of the beaches that would be considered for excavation and washing, the larger cobbles and boulders are located on top of and provide a protective armor for the underlying finer material. After treatment, these materials would be redeposited in a random, unsorted manner. The process of resorting would involve the redistribution of the finer material, the uncovering of the larger material and the settling and restabilization of materials that would be mobilized.

The completion of this restabilization process on an exposed boulder/cobble beach, such as KN-405 (Point Helen), would likely require one year (Hayes, personal communication). It may be slower in the lower tidal zone than in the upper and mid-tidal zones, due primarily to the increased exposure to high energy dynamic forces in the upper and middle intertidal portions of the beach. Moreover, the sediments in the lower tidal zone are not expected to be physically mixed by the rock washer. The completion of the restabilization process on a more protected and less armored beach, such as that of LA-18 (Sleepy Bay), would likely be slower, possibly requiring up to three years.

Many intertidal invertebrates breed in the springtime, with timing of larval release or spawning linked either directly or indirectly to the spring bloom of phytoplankton (Carefoot, 1977). Most intertidal species in Prince William Sound spawn successfully each year in the spring and summer, although a small amount of spawning of a few species may occur year-round. Off Kodiak Island, a significant proportion of colonization of artificial substrates was found to occur between March and September (Long, 1972). If restabilization of the beaches occurs during the late

summer or fall, the first major recruitment may involve one or a few opportunists late in the summer or early fall. For example, oligochaete worms have been observed in May 1990, in relatively heavily oiled beach materials in Sleepy Bay and at Point Helen. These opportunists may delay the development of a normal community if they competitively exclude other colonists the following spring. The recruitment of the "normal" mixture of species likely may not begin until the subsequent spring (beginning in mid-May or early June). Recolonization initiated during the spring would most likely result in the quickest attainment of a "normal" community.

When limpets and other grazing gastropods have been killed or removed and excluded from rocky shores, successive blooms of green and brown algae often have occurred. As a result of the competitive exclusion of other species from the community, recovery has been relatively slow—up to seven years (Nelson-Smith, 1975). The rock washing process would probably kill all gastropods in the treated portions of the beaches. The subsequent recolonization process may also involve the "green" phase of intense algal growth described by Nelson-Smith (1975).

Recolonization of a shore by animals can occur in four ways: 1) by migration of adults of mobile species from unaffected areas; 2) by direct settlement of planktonic spores or larvae dispersed by breeding organisms in unaffected areas; 3) by migration of juvenile stages of species with direct development (i.e., without planktonic larvae); and 4) rafting in of adults or their egg masses attached to floating seaweed or debris (Southward and Southward, 1978). Most intertidal invertebrates spawn by broadcasting progeny into the water column as plankton. Potential colonists for a clean beach can be produced great distances away and will drift to or actively seek suitable substrate for possible colonization. Other species do not broadcast their young into the water for dispersal, instead attaching their progeny to the rocks on the beach or carrying their young. Proximity of a clean beach to potential parents (brood stocks) becomes a very important controlling factor for these organisms, especially if the treated beach is large. Reintroduction of these species from the fringes of the cleaned beach would require that the species move onto the newly cleaned beaches. A relatively long time, several to many years, may be required for these organisms to reinvade and reinhabit all of the cleaned beach.

Some species do not routinely spawn every year, but, rather, spawn irregularly over 5- to 30-year cycles. These infrequently reproducing organisms include some predatory snails and sea stars, and some clams (D. Lees, personal communication). However, most of the species occur in either the lower intertidal or the subtidal regions that probably would not be directly impacted by a rock washing operation, although secondary effects of vessel operations and heavy machinery movements might stress the animals. Also, the sea stars and snails are motile and able to migrate from unaffected areas to affected areas.

Recolonization Projections. There are no site-specific data available from studies of beach excavations for use in estimating the recolonization rates of Prince William Sound beaches. The following projections, therefore, are based upon the observations made in other types of studies and from data collected elsewhere in northern latitudes. Table II-8 summarizes information obtained on recolonization of clean substrates following some kind of disruption, including oil spills in which dispersants or removal treatments were used. The studies listed in this table and described in more detail in Appendix A, were used to help predict recovery rates presented in this section.

Once the beach becomes stabilized and potentially recolonizable, the recolonization process would be expected to follow a pattern observed on clean materials in many studies performed throughout the world. The early colonists likely will be opportunists such as bacteria, colonial diatoms, brown and green algae, some infaunal worms, and epifaunal barnacles. The number of species will increase very quickly during the first three to six months, particularly in the spring, and will reach an equilibrium point during the following autumn beyond which few additional species will arrive. The assemblages will undergo a dormant season during the late fall and winter during which little recruitment will occur, followed by another burst of recolonization in the following spring. During the following spring, some early colonizing species will likely be replaced by late-arriving species, but the total number of species will not change to any great degree.

The rock washer will significantly deplete beaches of the detritus and other organic matter upon which many species feed. Reaccumulation of this material from phytoplankton, upland vegetation, and marine algal

Table II-8
Summary of Biological Recovery Rates for Previous Oil Spills

NAME	DISRUPTION FACTOR	BEACH TYPE	DEF. OF RECOVERY	RATE OF RECOVERY	REFERENCE
(1) Fouling panels Kodiak, Alaska	Sterile surfaces	Pressed asbestos wood panels	Equilibrium point in species colonization	Initiated in June 1969, 1970 Equilibrium point in 3 to 9 months	Long, 1972
(2) Lake Huron beach nourishment	Movement of gravel beach crushing/grinding	Cobble/Gravel/ Sand beaches	Compare with beaches before removal	8 months no difference between control & new habitats	Nester & Poe, 1982
(3) Puget Sound colonization curves	Sterile surfaces	Pressed asbestos wood panels	Equilibrium points for number of species	Clean sites--18-22 species at 7 months Contaminated sites--14-16 species at 7 months Both equilized at 18 months	Schoener, 1983
(4) Great Alaska Earthquake 1964	Uplift at sites	Mostly rocky outcrops/beach areas	Replacement of original species; equilibrium of species	Verrucaria/algae films--1 yr. 3 successive barnacle species replacements in 0-1-5 yrs. Mussel attachment replacements 3 algal species replacements of Fucus/Porphyra/Fucus 0-1-5 yrs.	Haven, 1971
(5) Torrey Canyon spill, England, 1978	Kuwait Crude oil 15,000 tons; toxic dispersants 10,000 tons	Intertidal Rocky shores, coves, beaches	Comparison with other areas not contaminated; species richness; wide range of sizes & age groups	Recolonization sequence, wave exposed areas Fucus dominant--5-8 yrs; other areas with residual toxicity, large scale mortality, removal of herbivores 9-10 yrs. for recovery	Southward & Southward, 1978
(6) Amchitka Atomic bomb tests 1969 & 1971	Atomic explosions uplift- ed 12cm & 3-110cm respectively	Bedrock & Boulder	Comparison of communit- ies with pre-tested com- munities	Approximately 3 yrs. for community to contain the same species & abundance as pre-tested habitats	O'Clair & Zimmerman, 1986
(7) Recovery & Recolonization Outer Continental Shelf	Any operational disturbance due to man's activities on the environment (oil exploration in outer conti. shelf regions)	Continental Shelf region	Return to pre-disturbance state; return to the range of variation compared to con- trol areas	None predicted; principles to consider: 1) type & size of disturbance, 2) seasonal fluc- tuations, 3) water movement, 4) selectivity of substratum for settlement, 5) biological inter- actions, 6) frequency of disturbance of substratum	Lissner, et al., 1988
(8) Amoco Cadiz spill Brittany 1978	Light Arabian & Iranian crude oil 223,000 metric tons; Bunker C 2000 tons and beach treatments	Bedrock headlands, sandy beaches, mud estuaries, mixed sand/gravel/cobble beaches, marshes	Return to normal popula- tion densities; no pathologies; amount of catches normal; mortalities normal; equilib- rium; hydrocarbons in tissue low; species numbers return	Oil removed (gravel/cobble) naturally in 1-1.5 years; Plants come back approx. in 1-2 years; animals come back approx. in 1-3 years; dominant species switching, still some imbalances & perturbances after 3 yrs	Marshall & Gundlach, 1990 Gundlach, 1981 Gundlach, 1983 Glemarec, et al., 1982 Bodin, et al., 1982
(9) Tamano Oil Spill Casco Bay, Maine, 1972	No. 6 fuel oil 100,000 gal algae removal & hot water treatment	Sleep rock shelves, outcrops, intrusions, cobble beaches	Comparisons between oiled & un-oiled control sites	1 yr. after--mud flats no new recruits; new shellfish at control sites; best recovery where no complete removal of seaweeds, un- cropped areas, areas not cleaned with hot water, less heavily oiled lower intertidal area	Marshall & Gundlach, 1990
(10) Amazzone Oil Spill Brittany 1988	Paraffinic medium oil 150 tons	Bedrock headlands, sandy beaches, mud estuaries, mixed sand/gravel/ cobble beaches, marshes	Measurements of different temperature washes; cost of rock washing technology Biological measure of recovery?	Results: higher temp. better than cold water; water + petroleum cut & surfactant, removal good but not complete with pebbles still \$50.00 per cubic meter of pebbles + transporting costs	Marshall & Gundlach, 1990

debris will dictate the colonization rates of these species, which include ambulatory species, epibenthic zooplankton, and infauna. Many of the epibenthic zooplankton are also important prey items for young salmonids. Slow recovery of these species may adversely affect the salmon from local streams.

Epifauna probably would locate stable suitable settling substrates before the infauna would find the sand and small gravel stabilized sufficiently for the latter to recolonize. The beach restabilization process involves the redistribution and winnowing of the finer material, and until this material ceases shifting, the prospective infaunal recruits would be faced with a relatively unfavorable environment.

Studies of the recolonization of new or denuded substrate following the Alaskan earthquake of 1964 (Haven, 1971), the U.S. nuclear tests on Amchitka Island between 1969 and 1971 (O'Clair and Zimmerman, 1986), and the TORREY CANYON oil spill of 1967 (Southward and Southward, 1978) all suggest that while an equilibrium point in the number of intertidal species observed may be reached in a relatively short period of time after a disturbance, return to comparable patterns of species dominance and distribution may take much longer to occur.

Haven (1971) noted an apparent change in the dominant barnacle species of the middle intertidal zone of areas uplifted during the 1964 Alaskan earthquake. Both *Balanus glandula* and *Semibalanus balanoides* had been present in the pre-earthquake intertidal zone, with *B. glandula* probably being the dominant species. Post-earthquake settlement of barnacles was almost exclusively composed of *S. balanoides*. However, five years after the earthquake, Haven found that *B. glandula* had once again become the dominant barnacle species*. Similarly, in 1965 an intertidal site that had been dominated by the brown alga *Fucus* was instead heavily covered by *Porphyra*. By 1968, *Fucus* had returned to its previous dominance.

O'Clair and Zimmerman (1986) discussed the effects of shoreline uplift caused by detonation of nuclear devices below Amchitka Island in

*O'Clair and Zimmerman (1986) have questioned Haven's identification of the two species of barnacles, but Haven's conclusions are presented here as stated.

1969 and 1971, and found that nine months after the second event, the intertidal shoreline remained in flux. Recolonization was still taking place, and algal and invertebrate species richness was found to be lower than they were under pretest conditions. Nearly three years after the uplift, intertidal communities were similar to those existing prior to the tests. In 1985, O'Clair found that with some differences, the new communities approximated those that had existed prior to the disturbance.

Southward and Southward (1978) documented marked differences in occurrence and distribution of intertidal species, particularly algal and herbivore colonizers, over a seven year timespan along rocky shores denuded by heavy use of oil dispersants in the TORREY CANYON spill. Three years after the spill, algal species such as *Fucus* had recolonized the effectively sterilized shoreline to a considerable extent. Seven years after that observation, however, apparently after herbivore populations had recovered, the *Fucus* cover was substantially reduced.

In summary, these studies indicate that while a functioning intertidal community similar in occurrences of species may be fairly quickly reestablished in a disturbed area, closer approximation to the preexisting structure appears to take a relatively much longer time to establish itself. The literature suggests an average time to equilibrium, or a stable number of species, to be about one to two years. In contrast, the time required for recovery to a comparably structured intertidal community varied from three to five years, with longer time periods also noted. Based upon the available information, therefore, recovery to reestablishment of a community composed largely of the same dominant species present before the spill and treatment, would be expected to become established three to five years after the beach becomes resorted and stabilized. For a newly cleaned and physically disturbed pebble/cobble/boulder beach requiring about two years to restabilize, the total elapsed time to recovery would be about five to seven years.

Siltation of Lower Intertidal/Subtidal Zones. Siltation per se cannot occur at the two candidate sites, because there is apparently little silt in the sediments to be washed. However, it is possible that some of the sand and granule material may be transported to the lower zones after being suspended by waves following washing. The volumes of sand involved are so small and probable dispersion so great that serious mortality of epifauna

or flora as a result of sediment suspension caused by the gravel washing process is not envisioned. The possibility of complete burial of lower intertidal/subtidal zones by gravel/sand because of gravel washing also seems remote for the same reasons. Sand is already present and in motion to some extent in these areas. An intertidal sand bar was present near low tide in Sleepy Bay on 26 May 1990 (see map in Figure I-13). Therefore, the fauna are obviously adjusted to some fluctuations in suspended and bedload sand volumes at Sleepy Bay, the candidate site with the finest sediments.

Siltation effects and burial could be a problem if sediments are washed on beaches that contain significant proportions of silt ($>\pm 10\%$) and fine sand ($>\pm 30\%$). Therefore, site-specific tests should be carried out at low energy areas that contain such sediments before washing is initiated. During the summer of 1989, use of high-pressure water washing to treat cobble beaches mobilized finer-grained sediments at some sites and washed them into the lower intertidal zone. Increases of 10 to 25 percent in the amount of fine-grained sediments in the lower intertidal zone after shoreline treatment were not uncommon, according to Exxon scientists.

As discussed above, the amount of weathered crude oil entering lower intertidal sediments associated with fine sediments from the upper shore probably is not sufficient to adversely affect the resident biota through toxicity. However, it should be pointed out that excavation of sediments containing significant quantities of silt may produce a more concentrated distribution of oiled sediments in the lower intertidal and shallow subtidal zones than a storm would, because of the possible lack of waves to disperse the sediments at the time of washing.

A majority of the plants and animals living in the lower intertidal and shallow subtidal zones of cobble/boulder shores in Prince William Sound are adapted to live in or on coarse-grained substrates and are possibly not well adapted to tolerate high suspended sediment loads over an extended period of time, although plumes of suspended sediment extending out from the numerous glacial streams are common phenomena in Prince William Sound in the summer months. Thriving communities of lower intertidal and shallow subtidal organisms exist near these stream mouths. Also, the stream that bisects the Sleepy Bay candidate beach must carry in suspended sediments during periods of high runoff. Introduction of large amounts of fine-grained sediments into the lower intertidal and shallow

subtidal habitats may render the substrate less suitable for habitation by the normal resident biota. This effect would be greatest on larvae settling from the plankton. However, established biota could also be affected.

Under a worst-case scenario involving the washing of silt-rich sediments, damage to the resident biota might result from outright burial by fine-grained sediments. Attached plants and animals possibly would be smothered. Motile animals, such as snails, amphipods, and starfish might also be buried, but most of them could dig themselves out of the sediment and survive. However, hard substrates on which many of the herbivores graze might be covered, diminishing the grazers' food supply. Most infauna can migrate vertically through several centimeters of freshly deposited sediment and so probably could avoid smothering if the amount of sediment deposited is not too great.

The burial and sediment texture changes associated with sediment mobilization from the upper shore and deposition in the lower intertidal and shallow subtidal zones, should it occur, probably would be of relatively short duration. A storm would be expected to remobilize the fine-grained sediments and move them offshore or back into the upper intertidal zone.

Disturbance by Vessels, Equipment, and Foot Traffic

The intertidal biota of exposed rocky shores are well adapted to the pounding of surf and the grinding of gravel by wave action. However, animals such as mussels, snails, and barnacles are readily crushed by foot traffic and movement of heavy equipment in the intertidal zone. It is reasonable to assume that in areas where the earth-moving equipment and rock washer moved, all plants and animals on the upper surfaces of rocks and most infauna in finer-grained sediments would be destroyed. This zone of destruction is likely to be larger than the area actually excavated.

The heavy equipment probably will have to be moved off the beach upon the approach of each high tide, requiring movement of large barges or landing craft up to the beach. Such large boat activities in the intertidal zone each day probably will disturb the abundant growths of large kelps and other macroalgae occupying the lower shore. However, these kelps grow rapidly, and any damage probably will be repaired within a few months.

Removal of Processed Fines

The rock washer probably will be able to clean sediments with a grain size larger than coarse sand and finer than 24 inches. The finer-grained sediments and flocs probably will be passed to the sediment separator device for further treatment. It may be difficult to remove sufficient oil from the finer-grained sediments to allow them to be returned to the shore. This oily sediment would be removed with the recovered oil and disposed of elsewhere.

The biological consequences of this change in the textural distribution of substrates in the middle and upper shore are uncertain. The upper and middle shores of exposed cobble/boulder beaches are not very productive biologically because of the instability of the substrate. However, in the middle intertidal zone, infauna often live in the finer-grained sediments below the surface layer of boulders and cobbles. With the destruction of their habitat, these animals would no longer be present on treated shorelines until natural geologic processes reestablish the sediment to near its original makeup.

Impact on Anadromous Fish Streams

Anadromous fish streams will benefit from the physical removal of oil if the oil threatens to leach into streambeds and affect the growth or survival of developing fish, or solidifies into asphalt pavement, thereby decreasing the amount of available spawning habitat. Even if oil is not located immediately adjacent to an anadromous stream it may still affect fish if flows occasionally cause the stream to meander laterally along the beach into an oiled area, or the movement of water, either on the surface or subsurface of the beach, causes oil to migrate into the stream. The effects of oil on these habitats and the species that use them are not well understood; therefore, a conservative approach appears to be warranted in removing the oil in the shortest time possible. However, excavation/rock washing has the potential to cause additional impacts if not carefully controlled. Potential impacts can include the removal of suitable spawning substrates, increased erosion, sedimentation of stream gravels, stream rechannelization, and altered hydrological patterns (stream flows, upwelling, and subsurface flows), all of which can render a formerly productive stream unsuitable for future use by salmon.

Air and Noise Pollution

Air and noise pollution will be an unavoidable component of any excavation/rock washing operation, although the extent to which such impacts are likely to cause environmental damages cannot be accurately predicted. It is primarily expected, however, from the use of heavy excavating equipment to remove contaminated sediments. In addition, a rock washer and associated support vessels or equipment (generators, heaters, boilers, etc.) could incrementally increase the amount of pollutants that are discharged into the air at a given site.

Conversely, noise pollution has a much greater potential to affect fish and wildlife species and human activities that occur in an area. The noise associated with an excavation/rock washing operation is likely to have little benefit, but could cause displacement of animals that normally use an area for important life functions such as birthing, foraging, nesting, or staging. This will result in a short term loss of habitat that should not be significant during non-sensitive time periods, and that support vessels and/or aircraft will access the area in a direct manner from offshore. However, human use will be affected in that recreationists and subsistence users will likely avoid an area where excavation/rock washing operations are occurring, although for reasons only partially attributable to noise generation.

Residual Oil

The performance objective for the rock washing is that, after treatment, the substrate should contain less than 800 ppm total oil. Assuming that this objective can be met with current technology, the upper shore will still contain some subsurface oil. A key question in evaluating the benefits of rock washing is whether this residual oil could produce any adverse biological effects.

As discussed above in Section II.A.5, petroleum adsorbed to sediments is less bioavailable and less toxic than oil in solution or dispersion in the water column. Several studies, discussed above, have documented that marine animals can tolerate and even recruit to sediments containing more than 800 ppm oil, particularly if the oil is weathered. In place, the subsurface oil is out of contact with any plants and animals and so does not pose a potential hazard to marine biota. However, the oiled sediments may be mobilized by storms and deposited in the lower

intertidal and shallow subtidal zones, though this has not been documented to date in Prince William Sound. The concentrations of petroleum hydrocarbons in these mobilized and redeposited sediments would be lower than in the sediments before mobilization due to dilution. Even at current levels of oil contamination of subsurface sediments, the concentrations of PAHs are generally below those known to cause adverse impacts, as discussed in Section II.A.2 and 5. Therefore, it is unlikely that these residual hydrocarbons would have any adverse effects on the biota of the lower shore. Furthermore, it is probable that most of the remaining subsurface oil will have weathered to the point where it no longer produces sheens.

II.B.3. WATER QUALITY

Increased Sediment Loading

Questions concerning sediment loading in the water column and rates of sedimentation are complex, and difficult to accurately determine without extensive research and careful consideration of a number of parameters that are probably beyond the scope of this investigation and report.

The beaches at the two candidate sites are composed of coarse sediments that will readily settle out of suspension. The water would clear up within a matter of a few hours, at most, of the end of operations at these two sites.

Secondary Spills of Fuel or Process Water

During the summer of 1989, there were 147 fuel spills throughout the spill site related to the cleanup activities. The average number of spills per month was 24.5. There were 949 vessels per month involved in cleanup in 1989, or an average of one spill per month per 39 vessels. We assume that 23 vessels are required to support one rock washer unit, if the unit has a throughput capacity of 100 yd³/hour. If four or five of these units are required to complete the necessary rock washing in the Sound within two months, we project that eight to ten fuel spills would occur in the Sound

related to the rock washer operation. There are no data on the size of oil releases in the 1989 incidents.

II.B.4 IMPACTS ON HUMAN INTERESTS RELATED TO EXCAVATION/ROCK WASHING

The benefits of excavation/rock washing on fishing will be to remove the oil from the beach matrix so that it cannot foul gear, taint fisheries products, or cause health concerns either to developing fish or human consumers. In this respect, excavation/rock washing is one of the most predictable means of assuring that oil is completely removed from the environment rather than remaining as a chronic threat. The expected impacts of the excavation and cleaning process include potential for increased sheening or resuspension of oiled particulates, which then can affect fisheries openings or harvests if the oil is not adequately contained. Silt plumes from the operation may also have an adverse effect on fishing. The disturbance by vessels, equipment, and personnel associated with the rock washing process and the increased sheening and siltation would displace recreational and subsistence uses in the area for the duration of the operation. Recreational uses and some subsistence uses could resume soon after the treatment process. Other subsistence activities would follow the natural recolonization of intertidal biota.

II.B.5 IMPACTS ON CULTURAL RESOURCES RELATED TO EXCAVATION/ROCK WASHING

The rock washing technique would obliterate the interpretive value of archaeological sites and probably damage or destroy artifacts. However, this negative impact can be avoided by an archaeological inventory of the rock washing areas prior to treatment and avoiding the specific archaeological sites within those areas during the rock washing operation.

II.B.6. IMPACTS OF WASTE HANDLING AND DISPOSAL FOR EXCAVATION ROCK WASHING

Introduction

This section describes potential environmental contamination pathways associated with handling and disposal of wastes that would be generated by excavation rock washing if it were to be conducted on an actual beach. These pathways may impact offshore or coastal waters, onshore surface waters, soils, or groundwater, and are associated with handling and disposal of the three primary waste streams: removed oil and sediment bearing wastewater, and oil-containing sludges. The human health and environmental impacts cannot be quantified, types of impacts that could develop via these pathways can be identified.

The risk of environmental contact associated with landfilling of the large volumes of oil-containing sludges generated by this technology is the primary potential environmental concern related to handling and disposal of excavation rock washing wastes. However, the ever-present risk of accidental spills, leaks, and other discharges through the handling and disposal of large volumes of any waste may also present potential environmental impacts.

Removed Oil

The primary pathway for potential environmental impacts from oil removed from beaches by excavation rock washing is accidental spillage. If spilled at the beach site, the oil could contribute to sheening or could recontaminate beach sediments, with impacts ranging from those of the oil contact to those due to additional cleanup measures required. If spilled during marine transport, sheen or a plume of floating oil could be produced. If spilled onshore or at the treatment, storage, or disposal facility, soils, groundwater, or surface water could be contaminated resulting in potential impacts on vegetation or human use, including potential human use of affected surface or groundwater.

Once successfully reclaimed or recovered, no further potential impacts would be anticipated, with the possible exception of impact on receiving waters of discharges related to such treatment. With properly controlled discharges, significant impacts should not occur. On the other

hand, if removed oils are landfilled, using the best available landfilling technology, the potential still exists for soil, groundwater, and surface water contamination due to seepage from the landfill if containment fails.

Wastewater (contains oil and suspended sediment)

Potential pathways for environmental impacts from oil and suspended sediment-bearing wastewaters are similar to those for the removed oil, but the potential impacts differ. Although oil content of wastewater is lower than that of the waste oil, volumes are much greater, and the suspended sediments themselves can create impacts. If spilled on the beach site, the primary impact would be creation of a suspended sediment plume and potential deposition of particulate matter, along with associated oil, on intertidal and subtidal zones. Spills occurring during marine transport could create sediment/oil plumes with a low potential for actual environmental impact. Spills occurring onshore or at the treatment, storage, or disposal facility could result in soil or groundwater contamination, or fouling of surface waters.

Once treated, little further potential for impacts exists. The wastewater should present no unusual treatment problems for a well-designed water treatment system, and properly controlled associated discharges should not create any significant impacts. However, any oil recovered from the wastewater presents the same impact potential as the oil initially removed from beach sediments.

Waste Sludge (contains oil)

The waste sludges have a higher potential for environmental impact than the removed oil or wastewater due to the concentrated nature of the material, relatively large volumes, and greater handling/treating requirements. Any accidental spill at the beach site has the potential to create heavy sediment plumes with associated significant deposition of particulate matter and associated oil on intertidal and subtidal zones. If a spill occurred during marine transport, significant oil/sediment plumes could result, although, as for the wastewater, the actual impact of such a plume in open water may be low. Potential impacts of onshore spills would be similar in character to those related to spills of the wastewater, but of greater potential magnitude in surface waters (due to concentrated nature

of waste) and smaller potential magnitude in low to medium permeability soil due to the high solids content. Likely land transport of this material prior to disposal poses additional opportunities for accidental spills onshore.

Since this material will likely require treatment prior to disposal, additional waste streams will likely be generated. Dewatering of the material will create additional oil and sediment containing wastewater with potential impacts similar to those for the wastewater initially generated by the process. Any additional oil removal step will result in creation of an oily waste with potential impacts similar to those for the oil initially removed from beach sediment, though the magnitude of impact has lower potential due to probable lower volumes.

Finally, it is anticipated that the bulk of the oiled sludge produced by the excavation rock washing process would be disposed by landfilling. Possible seepage from a landfill containing this oily sludge has the potential to impact nearby soil, groundwater, and surface water with a variety of potential effects on vegetation and human use, including use of the surface water or groundwater.

An additional environmental consideration is the use of landfill capacity. As current landfill capacity is taken up, new landfill capacity is created, generating new potential sources of soil, groundwater and surface water contamination.

III. SUMMARY

A technical committee was formed in May 1990 to investigate the environmental tradeoffs associated with excavating and washing oiled sediments remaining deeply buried along some sections of the Alaskan shoreline affected by the EXXON VALDEZ oil spill. The committee, comprised of Exxon, NOAA, and State of Alaska scientists, was charged with conducting a Net Environmental Benefit Analysis (NEBA) related to the advisability of excavation/washing in comparison to natural cleansing and application of treatment protocols approved by the Federal On-Scene Coordinator for use in 1990.

The NEBA committee selected two shoreline segments, Sleepy Bay on the north coast of Latouche Island and Point Helen on the southeast coast of Knight Island, as candidate locations to pursue field studies associated with the analysis.

The committee collectively outlined the range of environmental issues important to the analysis. The benefits and negative impacts of excavation and rock washing were researched in some detail, using both site-specific data from the candidate beaches and published studies on the fate and effect of oil and the impacts of physical disturbances to the shoreline. The results of these analyses can be summarized as follows.

How much oil is buried at what depths along the most severely affected sections of the coast? What are the prospects for removal by natural processes?

During the March/April 1990 shoreline assessment, 212 of the 1,134 shoreline segments surveyed had subsurface oil deposits thicker than 15cm and buried deeper than 15cm. Of 5,071 pits dug in the assessment, only 279 contained oil that had penetrated greater than 30cm, with 25 that had oil penetration greater than 60cm. The deepest occurrences of subsurface oil were found on coarse-grained beaches (boulder/cobble/pebble) along exposed shorelines.

NOAA studies at 18 stations in Prince William Sound over the six-month period from September 1989 to March 1990 indicated that, on the exposed shoreline segments most likely to be amenable to excavation, sediment reworking resulted in the removal of oil from the top 10-20 cm of

surface sediments. Data taken from Sleepy Bay and Point Helen reflected a 90% oil reduction in the top 30cm, but no discernible trend in oil reduction was evident below this depth. Exxon's winter monitoring study at 18 sites in Prince William Sound concluded that the concentration of total petroleum hydrocarbons (TPH) in subsurface sediments (generally >10cm) declined by 88% over the same period.

Using various survey methodologies, the estimated amount of oil remaining in subsurface sediments at Sleepy Bay, one of the candidate sites for excavation, was:

Gallons/meter of Shoreline	No. of Samples	Source
9.9	43	NOAA Oct-Feb Survey
5.0	13	Exxon Mar Survey
6.1	11	Exxon Jun Survey

Perhaps of more importance than the quantity of subsurface oil is the rate of natural removal which may be expected over the next few years. There have been numerous studies of previous spills in which the persistence of stranded oil has been surveyed. However, there are many factors specific to Prince William Sound that might alter the extrapolation of oil persistence curves from other spills to the EXXON VALDEZ. The factors that may speed natural removal processes in Alaska are:

- 1) Flocculation, the process by which fine-grained sediments adhere to the subsurface oil and make the oil less sticky and more biologically available.
- 2) Enhanced biodegradation, both naturally occurring and stimulated by the addition of nutrients.
- 3) Removal of surface oil during the 1989 treatment, which limited the formation of asphalt pavements.

The factors that may slow natural removal rates in Alaska are:

- 1) The relatively low wave energies relative to the grain size of shoreline sediments.
- 2) The initial high degree of contamination of some shoreline segments.

Oil removal is expected to be most pronounced early in the recovery period; this expectation is clearly being borne out by data gathered thus far through the various monitoring programs. NOAA estimates that virtually all of the oil buried in gravel shorelines should be removed, given no further treatment, in the periods of time indicated below:

Sheltered parts of Prince William Sound	10+ years
Sheltered outer Kenai	3-5 years
Exposed parts of Prince William Sound	2-4 years
Exposed outer Kenai	1-2 years

At what rate is subsurface oil being weathered?

Samples of subsurface oil were collected by NOAA from the two NEBA study areas and analyzed by gas chromatograph/mass spectrometry (GC/MS) to determine both chemical composition and weathering trends. Most of the subsurface oil in these samples was moderately to heavily weathered and altered significantly in both physical and chemical properties from the original state. Physically, the oil had become more viscous, less sticky, and would not readily sheen. Chemically, the oil had lost many of the light- to moderate-weight polynuclear aromatic hydrocarbons (PAHs), components which are of greatest toxicity to aquatic organisms. For example, the naphthalenes and phenanthrenes had been reduced by more than a factor of 100 when compared with fresh EXXON VALDEZ oil. Analysis of the saturate fraction of this subsurface oil showed strong evidence that microbial degradation had occurred. Overall, the subsurface oil had decreased in both concentration and toxicity and showed evidence of significant microbial degradation.

Will subsurface oil become exposed by wave action?

It is likely that there will be further removal of subsurface oil by wave action and shoreline erosion; however, these processes are most likely to

occur in the winter when sediment abrasion and thus natural cleaning of the surface is at a maximum. There is no general agreement as to the rate at which the oiled subsurface sediments would be exposed by these processes. Larger cobbles exposed during severe winter storms may remain with some surface oil contamination; the smaller sand, granules, and pebbles would rapidly be cleaned.

To what degree is water within the beach being contaminated by subsurface oil and thus exposing organisms to toxic hydrocarbon compounds?

Water within the beach ("pore water") comes in contact with subsurface oil as it moves through the interstitial space among oiled sediment particles. The prospect that pore water may become contaminated was investigated by the committee.

An Exxon mathematical model was used to predict the concentration of PAHs in pore water, which contacts subsurface oil deposits, and the rate at which tidal flushing would leach the water-soluble fractions of the oil. Using data on concentrations of PAHs in sediments collected in March 1990, Exxon predicted that concentrations of total PAHs in pore water would be generally below 20 ppb. These model results were confirmed by Exxon analyses of field samples of pore water collected in March at eleven sites in Prince William Sound. Only one sample contained PAH levels greater than 10 ppb and only three reflected levels greater than 1 ppb. Two of the three highest values were for samples collected from Sleepy Bay. All observed levels of pore water contamination are below concentrations known to be acutely toxic to marine organisms.

An additional twelve water samples were collected by NOAA at the sediment/water interface during falling tides from Sleepy Bay in May 1990. Total PAH concentrations in these samples were all less than 1 ppb. The rapid dilution of the pore water as it mixes with clean interstitial and shallow subtidal waters should result in PAH concentrations that pose little or no toxic hazard to marine organisms on the lower shore and in subtidal waters.

To what extent can sheens be produced by subsurface oil? If such sheens are produced, what adverse effects can be anticipated?

The committee investigated the frequency, magnitude, composition, and effect of oil sheens likely to originate from subsurface oil. Observations by ADEC and Exxon show a declining trend in both sheen frequency and volume throughout Prince William Sound. The downward trend in Exxon data is more pronounced, possibly due to the elimination of non-Prudhoe Bay crude sheens from the data set. On a weekly basis, the volume of sheens from EXXON VALDEZ oil is now well below the present level of petroleum hydrocarbons introduced to surface water of Prince William Sound from other sources (vessel traffic, combustion, natural organics, etc.).

NOAA chemical analysis indicates that the natural weathering of subsurface oil has rendered the oil both less toxic and much less capable of producing sheen. As long as the oil remains physically stable in the shoreline, sheen frequency should be minimal. A temporary increase in sheening would likely be produced either by excavation or by intense winter storms. Sheens produced by excavation could be expected to be controlled in light to moderate weather conditions. While control of storm-induced sheens is unlikely, the range and effect of such sheens would be limited by natural dispersion during the storm event. NOAA studies in 1989 indicated that only in unusual weather conditions would convergence zones have the potential to concentrate free-floating oil into popweed windrows to the extent fishing gear might be contaminated. The threat of exposure to birds feeding at these windrows is likely to be small as exemplified by the lack of reports of oiled marine birds this year.

In summary, subsurface oil is relatively stabilized and insulated from exposure to vulnerable resources through sheening. Adverse effects on birds, fish, wildlife habitat, or human uses are not expected to originate from sheens produced by subsurface oil.

What is the near- and long-term fate of subsurface oil?

Subsurface oil that persists in the shoreline will eventually be degraded by indigenous bacteria. However, prior to the complete microbial breakdown of oil buried deep within the shoreline, other processes may be important in controlling the intermediate distribution and fate of the oil.

Flocculation is one process that has been proposed by Exxon as being an important mechanism for enhanced natural removal and dispersal of subsurface oil. The flocculation process has been demonstrated in laboratory studies, and in the field some subsurface oil appears to have taken on a more weathered, smeary texture indicative of floc formation. However, the rate of flocculation and its relative importance, particularly in the removal of heavily oiled subsurface sediments, is not known.

There is some concern that the fine-grained fraction of oiled subsurface sediments may be exposed by erosion and deposited in the nearshore subtidal environment. Since there are few data available to evaluate this potential risk, a diving survey was conducted by ADEC in June 1990 to collect subtidal sediments along a transect out to 100m off both Point Helen and Sleepy Bay. Total PAHs in these subtidal sediments were 0.1-9 ppb off Point Helen and 1-130 ppb off Sleepy Bay. This limited sampling would indicate that deposition of oiled sediments, derived from either subsurface or surface sources, may be minimal.

What are the potential effects of rock excavation on the shoreline substrate?

There is great variability in sediment grain size and shoreline exposure in Prince William Sound, and therefore the effects of excavation and rock washing on the structure of the intertidal zone would vary considerably from location to location. Shoreline segments that contain high concentrations of subsurface oil are also generally exposed to moderate or high wave energy. The upper part of the intertidal zone in these locations is affected by the erosion and deposition of high-tide berms, as shown through analysis of data obtained during the Exxon, NOAA, and ADEC winter monitoring programs. The middle and lower intertidal zones are less affected, particularly if a cobble/boulder armor is present, such as on Point Helen, one of the candidate sites for rock washing.

Using data from the winter monitoring programs and case histories from other studies, it is predicted that, if the material were removed from the upper one-third of the beach and replaced in approximately the same position from which it was taken, the upper berms at Point Helen would reestablish themselves after two or three medium-sized storms. The re-armoring process in the middle and lower part of the shoreline would require a few more storms, possibly covering a period of one to three years.

For Sleepy Bay, which is more sheltered but also is composed of finer-grained sediments, the upper surface sediment resorting should occur in less than one year. However, because the middle portion of the beach changes more slowly, complete reestablishment of the original profile and sediment resorting may require up to three years, though it may take place sooner. Recolonization by intertidal organisms would be delayed during these periods of sediment restabilization.

Loss of fines is not expected to be of concern, mainly because of the relatively small percent of sand-sized materials in the upper zone on most beaches in Prince William Sound. Because the sand exists primarily as a matrix to the already fixed framework of the beach, there should be no impact of its potential loss on beach morphology or erosion. There were concerns that the loss of sand might change the hydraulics of the beach, but the magnitude or consequences of this impact are unknown.

What are the effects of subsurface oil and excavation on the recolonization by intertidal communities?

In the areas where excavation is being considered, the intertidal zone can be divided into three subzones on the basis of the distribution of biological communities. The upper intertidal zone, generally the location of the highest concentrations of subsurface oil, is normally not inhabited by a very rich biological community because of relative dryness, sediment mobility, and lack of food.

The middle intertidal zone contains a more rich and diverse biological community. Observations made this spring and summer indicate that these communities are recovering from the oil and treatment activities. Oil concentrations of the surface sediments in this zone are generally low and, as discussed earlier, toxic impacts from the discharge of groundwater through oil-contaminated sediments across this zone are not expected to be significant. Because most of the plants and animals in this zone live in the top 10-15cm, there is no pathway of exposure to subsurface oil other than oil exposed during erosional events. To the extent the oil remains buried, it poses no serious risk to intertidal communities in this zone.

The lowermost intertidal zone has the greatest biomass and species diversity. In most cases, this zone is showing evidence of recovery and only

very low concentrations of oil occur in the surface sediments. The lower intertidal zone would be least impacted by the residual subsurface oil.

With the information available on the likely zone of disturbance by excavation and rock washing, it is assumed that few organisms in the upper and middle intertidal zones would survive. There may also be impacts to these zones resulting from the traffic of equipment and people on the shoreline. It is likely that these surface impacts would extend to some degree into the relatively rich lower intertidal communities.

NOAA estimates that three to five years would be required for biological recolonization after the shoreline stabilizes. Adding one to three years for stabilization, the total recovery period after excavation is estimated to be four to eight years. If excavation does not occur, NOAA estimates recolonization will occur in two to five years at Point Helen and three to six years post-spill at Sleepy Bay.

What would be the secondary impacts from excavation and rock washing?

Increased sediment loading in the water column would be unavoidable during excavation and replacement. Coarse material would settle out readily, although it is likely that oiled silts and clays would settle slowly and might be transported along the beach by tidal currents.

Secondary spills of fuel and process water were estimated using the spill rate of cleanup activities in 1989. Assuming that four or five rock washing units were active for a two-month period, an estimated eight to ten fuel spills would occur.

Excavation and rock washing would disturb wildlife with work activity and noise for six weeks or longer in each work area. Sources of disturbance include personnel, vessels, equipment, and aircraft. Traffic in the intertidal area may further affect the recolonization process.

Exxon estimates that excavation and rock washing at Sleepy Bay would generate 12,000 gallons of skimmed oil/water mixture, 168,000 gallons of wastewater, 500,000 gallons of sludge waste, and 300,000 pounds of air emissions. Fuel consumption is estimated at 400,000 gallons.

What would be the impacts on human use of the shoreline and nearshore waters should subsurface oil not be removed? What would be the related effects of excavation/rock washing?

The State of Alaska indicates that any of the shoreline segments which are candidates for excavation and rock washing are in areas of moderate to high human use. These areas are used throughout the year for recreation, subsistence and commercial fishing, and are of significant cultural importance. Subsurface oil has some capacity to pose an episodic threat to these uses of the shoreline and nearshore waters.

Although sheens are declining in Prince William Sound, and the relationship between sheens and subsurface oil is tenuous in non-storm conditions, commercial fishing in the immediate vicinity could be affected in the event sheening does occur. Episodic releases of subsurface oil may contaminate subsistence fisheries, interfere with shore-based commercial and recreational fishing, and impair use of the shoreline for recreation. Large amounts of subsurface oil can impact recreation and subsistence users who dig fire pits in the upper intertidal zone.

Excavation/rock washing is one of the most predictable means of assuring that oil is removed from the environment rather than remaining as a potential source for episodic exposure during winter storms. The expected impacts of the excavation and cleaning process include potential for temporary sheening or resuspension of oiled particulates, creation of silt plumes, and disturbance by equipment and personnel. These impacts can be mitigated by proper containment of sheens and timing of operations to minimize impacts to resources and users. Recreational and some subsistence uses could resume soon after the treatment process. Other subsistence activities would be delayed four to eight years until natural recolonization of intertidal biota occurred.

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APPENDIX A: CASE HISTORIES

A variety of case histories were reviewed in which biological recovery was monitored after oil spill events, or in which unpopulated materials were introduced into the marine environment and recolonization rates monitored. It is recognized that differences, sometimes substantial in nature, exist between the case histories presented here and the situation in Prince William Sound. However, in the absence of other more directly applicable data, these provide an information base from which projections of impacts and recovery might be derived. The studies described below are also summarized in accompanying tables.

No further treatment case histories

1. The IRISH STARDUST Spill

On 24 January 1973, the freighter IRISH STARDUST grounded on Haddington Reef in British Columbia. Two fuel tanks were ruptured, and approximately 200 tons of heavy "1,000 second" fuel oil spilled into Broughton Strait. Major cleanup operations were undertaken in most of the oiled areas, but one of the more contaminated bays was sufficiently isolated that it could be left undisturbed for scientific study. The recovery of this untreated bay was tracked for a period of one year, with both chemical and biological observations recorded and reported in Green et al. (1974).

Although the study period was relatively short for assessing recovery, it was noted that only those species that had been in direct contact with the oil appeared to have been adversely affected (e.g., limpets, periwinkles, isopods, rockweed, marsh grass). No species was completely eliminated, and there were indications of recolonization. The authors concluded that within the limitations of the study, it appeared there would be no permanent effects on the biological community.

The major mechanism for altering the chemistry of the oil was found to be bacterial. The asphalt-like covering that remained after bacteria degraded the paraffin portion of the oil was apparently more susceptible to physical weathering, and was slowly disappearing. Approximately 90-95% of the oil was estimated to have been removed by natural processes, and

recovery from the relatively minor biological damage was judged to be underway.

Cretney et al. (1978) tracked the chemical fate of the spilled oil for four years following the grounding. Six visits were made to the site over the period. The composition of the oil was first altered by loss of lower molecular weight fractions through dissolution and evaporation. In the first year, biodegradation almost completely removed n-alkanes. By the fourth year, pristane and phytane were nearly completely gone. The most resistant components appeared to be the non-n-alkane compounds in the nC₂₈₋₃₆ range.

2. METULA Spill: Microbiological Studies

The oil tanker METULA spilled approximately 51,500 tons of Arabian crude oil and 2,000 tons of Bunker C oil in the Strait of Magellan between Patagonia and Tierra Del Fuego on 9 August 1974. There was no cleanup performed, and this site serves as a natural laboratory to monitor the long-term persistence of oil. The location of the spill has some similarities to the EXXON VALDEZ spill.

Some of these similarities are:

- temperature
- ice cover
- some beach sites (i.e., mixed sand and gravel, deposited by glacial action)
- climate
- exposure of beaches
- and fetch and wave conditions.

Because of these characteristics, the two oil spills can be used as comparison models to some degree (Marshall and Gundlach, 1990).

The oil spill was studied by Baker and reported little damage from oil in the months immediately following the spill, but Straughan indicated reduction in distribution and abundance of species due to the presence of oil five months after the incident (Straughan, 1976). During this time, the inventory of cobble/gravel/sand type beaches had none to one or two species living at these kind of sites.

Six and one-half years after the METULA spill, the sites again were inventoried. It was found that on cobble and gravel type beaches only algae and mussels attached to gravel. The investigators indicated that areas previously impacted, but now free of oil, were found to have a tremendous repopulation by mussels (Gundlach et.al., 1982).

Colwell et al. (1978) studied the microbiology of the bacteria associated with biodegradation of the oil that had been left along the shorelines of the Straits of Magellan. They arrived at five conclusions:

- (1) The METULA petroleum contamination selectively stimulated certain bacterial species and so induced major shifts in the population structure.
- (2) Temperature did not appear to be a limiting factor for biodegradation. In fact, there were some indications that cold-tolerant bacteria were more efficiently metabolizing the crude oil at 3°C than at 22°C.
- (3) The biodegradation process in the marine environment is a slow process, possibly limited by nutrients and by physical access to degradable compounds in aggregations or tarballs.
- (4) Weathering can be a significant removal process in concert with microbial degradation. However, neither mechanism is effective if oil is deposited and buried, or forms asphalt layers or tarballs.
- (5) The weathering and microbial action may contribute significantly to formation of polar compounds.

3. U.S. Air Force Fuel Depot Spill, Searsport, Maine

In early March 1971, a pipeline ruptured at the U.S. Air Force Fuel Depot adjacent to the western shore of Long Cove in Searsport, Maine. At least 14 tons of a mixture of JP4 jet fuel and No. 2 heating oil was spilled, and reached the intertidal zone of Long Cove on March 16. Mayo et al. (1978) reported that in 1974, the loss of the standing stock of resident softshell clam, *Mya arenaria*, due to the spill was estimated to be greater than 85%. Chemical analysis of sediments showed substantial contamination with light to medium refined hydrocarbons.

By 1976, recovery of the *Mya* population was found to be taking place, but at a very slow rate. Animals were found only in well-drained portions of the upper intertidal zone. Comparison to chemical analyses of sediments

showed that clams were found in only one area with petroleum hydrocarbon concentrations exceeding 100 ppm. In addition, very few clams were observed to be living in sediments with residues in the range of 50-100 ppm (six sites). The remaining 44 sites were populated with clams but had hydrocarbon residue concentrations at 49 ppm or less.

4. ARCO ANCHORAGE Spill

The tanker ARCO ANCHORAGE ran aground in Port Angeles Harbor, Washington, on 21 December 1985. Approximately 239,000 gallons of Alaska crude oil were spilled, and the the south-facing shore of Ediz Hook was impacted by both the spill and the subsequent cleanup activities. The latter resulted in physical disturbance of the beach between February and early April, 1986. Data collected as part of the Ediz Hook monitoring program indicated that more than 74% of the residual crude oil in sediments was removed by physical agitation during the beach reclamation process. Blaylock and Houghton (1989) asserted that the reclamation efforts undoubtedly decreased the retention time of oil in the sediments from that expected based on natural weathering processes alone, especially for deeper material.

A study (Word et al., 1987) cited by Blaylock and Houghton (1989) estimated that it would take 18.5 months for the intertidal beach to reach background hydrocarbon levels, and nearly four years for complete biological recovery. Blaylock and Houghton concluded that recovery at agitated transects likely occurred much more rapidly than in the absence of beach agitation. In particular, they found that recolonization by bivalves would probably not have occurred as quickly without the rapid reduction in sediment hydrocarbon concentrations that followed sediment agitation. The authors suggested that sediment chemistry and the biological conditions relative to infaunal biomass, density, and diversity indicated that 1988 conditions were similar to pre-spill conditions.

Mancini et al. (1989) affirmed these observations, noting that while it was not possible to conclude that biological recovery was "complete," available data clearly indicated it was well underway.

Miller (1989) examined physical and chemical recovery of intertidal and subtidal sediments from the ARCO ANCHORAGE spill, and noted that residual oil concentrations in Ediz Hook sediments declined steadily

between March 1986 and July 1987. He also described the "armoring" of the pre-agitation beach by a surficial layer of cobbles on which barnacle encrustation was evident. This indicated that the cobbles were moved infrequently. The armor layer was breached by beach reclamation activities, surface cobbles becoming mixed with deeper sediments during beach agitation. The agitation equipment also left ridges in the beach surface roughly parallel to the shoreline. Miller commented that photographic documentation indicated little residual evidence of the beach ridges in May 1988, and much of the armor layer had been reestablished by this time (within two years of the beach disturbance).

5. TORREY CANYON Spill

Nelson-Smith (1977) discussed the recovery of British shorelines that had been affected by oil spills, including those that had been impacted by both oil from the TORREY CANYON and the ill-advised use of dispersants during the cleanup operations. Although noting that the coast of Cornwall was not rigorously resurveyed during the later stages of recovery, Nelson-Smith casually observed that within two to three years of the spill, the less seriously disturbed areas had regained their normal appearance, although some less common inhabitants were still rare or missing. The worst sites were superficially indistinguishable from normal after six to seven years with the exception of a higher density of limpets.

More generally, Nelson-Smith tentatively concluded that the rate of recovery from oil spills and damaging cleanup treatments depended very largely on the extent to which the numbers of limpets have been reduced and the speed with which they can reestablish themselves densely enough to control the resulting bloom of large algae. This, in turn, depends not only on the nature of the oil spilled and any cleansing treatments, but also on the extent of the damage and location of the affected shore with respect to sources of adult or larval animals able to recolonize the damaged area. The time scale of the process depends on how "recovery" is defined: if this is accepted as meaning a reinstatement of the previously dominant community, even if some minor members of the ecosystem may still be absent or fewer, then the oiling or cleaning incident may be less serious than a climatic aberration such as a hard freeze. Nelson-Smith noted that while recovery of intertidal communities from the TORREY CANYON

incident seemed to have recovered after seven years, even impeded by destructive cleanup techniques, those animals most affected by a severe cold spell showed little sign of regaining their previous status on the worst-affected shores after 12 years.

6. Ecological Monitoring in Port Valdez, Alaska

Cowell and Monk (1979) discussed baseline surveys in the Port Valdez region of Prince William Sound and noted the technical and scientific problems associated with ecological monitoring there. In particular, they discussed the lack of understanding of the processes governing the Alaskan rocky shore ecosystem and the paucity of data on the natural stresses controlling temporal and spatial variation in populations. In addition, taxonomic difficulties, particularly in littoral macro-algae, compounded survey problems. Although the sheltered environment of Port Valdez differs from that encountered in central and southern Prince William Sound, many if not most, of the intertidal species are the same, and many if not most of the problems encountered by Cowell and Monk are the same as those that complicate an assessment of the proposed rock-washing activities.

Cowell and Monk found a distinct gradation in size of the limpet *Collisella pelta* with location in the intertidal. That is, a clear increase in the size of the limpets was observed with increasing height on the shore, and it was evident that very young limpets occurred only on the lower shore. Three possible explanations for this observed trend were given:

- (1) Recruitment may occur over a large part of the shore, but only individuals which have settled on the lower shore may survive and older animals migrate upward.
- (2) Recruitment may be limited to the lower shore and be followed by slow migration up the shore over a number of years.
- (3) Annual limpet migration could occur, in which the winters are spent in the subtidal and migration into the intertidal could occur during the summer. The observed size distribution would be explained if the distance travelled by the limpets was in direct proportion to their size.

Colwell and Monk did not successfully elucidate the physical and biotic factors controlling the intertidal ecology near Port Valdez. Some links to salinity and exposure were suggested but data were limited. Unfortunately, examination of shores geographically more distant from Valdez was intended but not accomplished. This information would have been more relevant to the rock-washing evaluation.

7. Baffin Island Oil Spill (BIOS) Project

The BIOS Project was a multidisciplinary program of research on arctic marine oil spill fate, effects, and countermeasures. It was sponsored by governmental and industry agencies from four nations and took place over a four-year period between 1980 and 1984 on the northern end of Baffin Island, Northwest Territories, Canada. The major components of the study involved the controlled releases of oil to two complementary beaches, where the consequences of treatment with dispersants were compared to no treatment.

Sergy (1985) discussed results of the BIOS study. He commented that despite the significant accumulation of hydrocarbons and aside from acute effects, the overall magnitude of impact on subtidal (3-10m water depth, therefore well below the anticipated zone of major impact in rock-washing) was that, over two years following the releases, the beached oil (as well as the dispersed oil) did not cause any large-scale mortality of benthic biota or any significant change in benthic infaunal community structure. Relatively minor effects were noted in only a few of the species examined (temporary reduction in abundance, some reproductive impacts, changes in length-weight relationships).

8. San Francisco Bay Oil Spill

On 18 January 1971, two Standard Oil tankers collided under the Golden Gate Bridge, spilling 840,000 gallons of Bunker C oil into San Francisco Bay coastal waters. Pre-oil and post-oil transect data were compared by Chan (1975), and it was estimated that 4.2 to 7.5 million marine invertebrates, mostly barnacles, were smothered by the spill. In subsequent observations from 1972 to 1974, the sample counts of invertebrates had equalled or surpassed pre-oil transect levels. No long term effects of the spill were noted in any of the marine species.

In 1974, less than 5% of the oil spilled was estimated to be remaining on rocky surfaces. Good recruitment of marine organisms at oiled transects was observed, particularly for barnacles, mussels, periwinkles, and limpets. Decreases were seen in some reef organisms such as crabs. In a discussion of monitoring results five years after the spill, Chan (1977) noted some unusual population lows for a few intertidal species, but he attributed these to natural physical phenomena such as large waves. Chan called the overall health of marine life in the intertidal good. Species such as barnacles, limpets, mussels, periwinkles, starfish, turban snails, and shore crabs all showed steady population recruitment in the five years after the 1971 spill.

9. ARROW Spill at Chedabucto Bay, 1970

On 4 February 1970, the tanker ARROW grounded on rocks and spilled approximately 10,000 tons of Bunker C oil in Chedabucto Bay, Nova Scotia. The topography of this region consists of rocky outcrops, eroding till cliffs, and gravel and mixed sediment beaches. Six years after the spill, Thomas (1978) attempted to determine the effects of the spill on intertidal communities, but was confronted with the common problem of a lack of information on normal (pre-spill) community structure and species abundances. This was compounded by the fact that the spill occurred under winter conditions and in the presence of sea ice. Thomas found that on rocky shorelines, although there were no significant differences in intertidal distribution of species between oiled and control sites, a consistent difference in species diversity was observed. It was noted that this is typical of pollution-stressed communities, but also that it was interesting that the difference persisted six years after the spill event, even in areas that had little evidence of oil remaining. Six of the ten most common species were more abundant at control sites, and biomass of algae was found to exceed that at oiled sites by a factor of three.

Cleanup of the shoreline in the ARROW spill included manual pickup and use of heavy equipment to remove oiled sediments. In some cases, clean gravel was brought in to replace oiled material that was removed (Marshall and Gundlach, 1990). Thomas (1978) commented that it appeared that cleanup on rocky shores did not speed recovery and in fact may have hindered it, while that in finer-grained environments was less

clear in its long-term impacts. It was noted that in the latter areas, if techniques could be improved to be less intrusive, then cleanup should help to minimize oil spill impacts.

10. GENERAL M. C. MEIGS Oil Spill, 1972

In January 1972, the troopship GENERAL M. C. MEIGS broke loose under tow and came ashore on the northwest coast of Washington. Navy Special fuel oil was spilled on a rich intertidal community. The ship continued to release oil to this habitat for more than five years, first in the form of fluid which came ashore on the shallow rock shelf and intertidal margins, and later in the form of discrete globules, floating into Wreck Cove where it became incorporated into the coarse sand beach (Clark et al., 1978).

The initial survey of the plants and animals in 1972, just after the spill, revealed no major damage or recent extensive mortalities in the animal populations, with the exception of sea urchins (*Strongylocentrotus purpuratus*). The latter lost spines from their aboral surface, and shortly after the spill some individuals had lost nearly all their spines. There were also some indication of direct mortality. Macrophytic algae in the affected area lost fronds and showed signs of bleaching, which were taken as signs of damage. By analyzing the tissues of mussels and algal species, it was noted that there was moderate uptake of hydrocarbons which occurred approximately nine months to one year after the spill. In 1973 there was a decline of the abundance of live barnacles, mussels, and colonial anemones. Sea urchin pathologies continued to be observed, as was bleaching in algal species. Brown algae became the dominant form over the mid-intertidal zone. Four years later, in 1977, the abundance of barnacles increased, and the other species of plants and animals continued to maintain their lower level of population numbers. No species completely disappeared, nor were abundances extremely low. The other algal types replaced the brown algae as dominant in the region. Hydrocarbons in the tissues were still found at measurable concentrations, probably due to recontamination by tar balls.

The definition of recovery in this case involved visual investigation and assessments of animal and plant communities, compared to sites in the region that were not contaminated with oil.

Overall, there was a general decline in the abundance of organisms, except in the barnacle population, over a five-year period of time. Sea urchins suffered up to three years (1975), but seemed to recover afterwards. This study indicated that there are species that are more sensitive than others to oil, and that the abundances were lowered after exposure, but the community reached a point of equilibrium after three to five years.

11. NESTUCCA spill, coasts of Washington and British Columbia

The NESTUCCA spilled Bunker C oil on the coasts of Washington and British Columbia. Monitoring for the National Park Service along the Olympic Peninsula has been conducted.

The Environmental Protection Service (EPS) also monitored recovery along the southwest coast of Vancouver Island where heavy oiling and various treatment technologies were used. On Vancouver Island, eelgrass beds were impacted and mortalities among other organisms were observed. One one beach an attempt was made to dig up the beach material and burn the oil residue. This operation was not successful since the material would not burn. One year later, the biota in the treated beach appeared to be similar to that of adjacent beaches that were not treated (L. Harding, EPS, personal communication).

12. IRINI Oil Spill, Stockholm Archipelago, Sweden, 1970

Medium and heavy fuel oils were spilled from the tanker IRINI in October 1970. About 1000 tons of this material drifted onto the shores, and an estimated 400 tons went into a small bay where it killed most of the littoral fauna. Much of the oil was collected or dispersed by booms, mechanically, or through the use of solvents. Oil was still visible under the surfaces of sandy beaches and stones. The oil degraded much more rapidly on rocky shores than in the sandy beaches. Notini (1978) reported recovery of the littoral community during the period 1971-1978. No oil effects were noted on macroalgae in 1971. Littoral fauna recovered more slowly, but had returned by 1976 (Marshall and Gundlach, 1990). The recovery period for this habitat, then, was about one to six years.

Rock washing case histories

1. The Alaskan Earthquake, 1964

On 27 March 1964, an earthquake of unusual severity struck the Prince William Sound region of Alaska. The earthquake, measuring between 8.3 and 8.6 on the Richter scale and lasting for over three minutes, caused extensive damage over a wide area and substantially changed the character of the shoreline in Prince William Sound. Both vertical and horizontal elevations in landmasses and the seafloor occurred. As a result, zones of distinct tidal communities were displaced and new zones were defined. Studies of the recovery of shoreline communities in Prince William Sound could offer general insights into mechanisms of ecological succession relevant to assessment of intertidal recovery after rock washing.

Haven (1971) surveyed Prince William Sound in 1965 (fifteen months after the earthquake), and observed that although recovery of shoreline biota was widespread, the intertidal areas had not yet settled into a climax community. As evidence of this, he cited (1) the lack of post-earthquake growth of the lichen *Verrucaria*, which normally defines the upper limit of the intertidal zone; (2) in areas of maximum uplift, the dominance of the red alga *Porphyra* in zones normally dominated by *Fucus*; (3) the reversal in dominance of two *Balanus* barnacle species in certain intertidal areas; and (4) the attachment of new mussel recruitment to algae rather than hard substrate.

Haven (1971) returned to the area in 1968 (four and one half years after the earthquake), and found that recovery to preearthquake community structure was much further advanced. It appeared that *Verrucaria* was establishing itself in the new upper intertidal zone, dominance of algae and barnacles had reverted to the previous conditions, and mussels were attached primarily to rocky substrates or barnacles. Haven concluded that with a few exceptions, the intertidal had returned to essentially its pre-earthquake condition in about four and one-half years.

2. Underground Nuclear Testing in the Aleutian Islands

Two nuclear underground tests were detonated on the Aleutian island of Amchitka on 2 October 1969, and on 6 November 1971. O'Clair and Zimmerman (1986) visited the island and studied changes there over a

nearly fourteen year period. Portions of the rocky intertidal shoreline were uplifted 12cm by the first explosion, and 3-110cm by the second. Although most of the affected shoreline was bedrock or boulder in character, some intertidal species observed were the same as those encountered in much of Prince William Sound (e.g., *Fucus distichus*, *Mytilus edulis*, *Balanus glandula*). O'Clair and Zimmerman (1986) found that nine months after the second detonation event, the intertidal shoreline remained in flux, with recolonization still taking place and invertebrate and algal species richness decreased in the upper intertidal zone. Although intertidal communities similar to pretest assemblages were observed 33 months after the uplift of the shoreline, upper limits of the intertidal zone were below those that had existed previously. O'Clair and Zimmerman suggested that one reason for this may have been the gradual sporophytic reproductive process of the dominant macrophytes.

O'Clair returned to Amchitka Island in 1985, nearly fourteen years after the last test. He found that with some differences, the new communities approximated the biota that had existed prior to the disturbance. However, the upper extension of the intertidal, which in 1974 had appeared to be lower than the original limit, remained at essentially the same level.

It was concluded that in regions of uplift like that experienced on Amchitka Island, it normally takes three years before community development within the new uplifted community approximates the same species composition and relative abundances that had existed previously.

3. Review of Recovery and Recolonization of Hard Substrate Communities of the Outer Continental Shelf

This review was prepared for the Minerals Management Service and was published as Lissner et al. (1988). Although it was intended for use in evaluation of California outer continental shelf leasing areas, it contains a good summary of ecological theories of recovery and recolonization. As such, it provides insights into processes that would be operative in any marine environment, including that of gravel beaches in Prince William Sound that are under consideration for rock-washing.

Six factors were listed as influencing the recovery/recolonization process in marine ecosystems:

- 1) the type and size of the disturbed patch
- 2) seasonal fluctuations in abundances of propagules
- 3) water movement, including boundary layer flow, currents, and storm surge
- 4) selectivity of propagules for substratum characteristics during settlement
- 5) biological interactions occurring among the organisms colonizing patches
- 6) frequency of disturbances of the substratum

Some discussion was devoted to defining recovery/recolonization from an operational perspective, and this is relevant for the rock-washing assessment as well. In the extreme case, complete recovery from a disturbance could imply that a community has returned to its pre-disturbance state for all parameters such as species composition, species diversity, abundance of organisms, and age structure of populations. However, it was noted that many recent studies have defined benthic communities as consisting of a mosaic of patches varying in size, age, species composition, and disturbance, and a less rigorous definition was said to be both more appropriate and more practical. Lissner et al. (1988) used the definition of recovery as being complete when the variation in a disturbed area has returned to a range of variation observed within undisturbed control areas.

4. Colonization Curves for Clean Artificial Substrates

Long (1972) reported results of fouling accumulation studies at three sites off Kodiak Island, Alaska at depths of 5, 15, and 30 meters. Clean pressed asbestos panels were submerged in June of 1969 and 1970. Schoener et al. (1978) compared the rates of colonization of hard artificial substrates at numerous sites in tropical, subtropical, temperate and boreal latitudes, including the sites off Kodiak Island. The colonization curves were steeper (more species arrived quicker) in tropical and subtropical areas than in more northerly sites.

The substrates deployed off Kodiak Island in June quickly were colonized by four to five species within two months. Barnacles, mollusks, tubeworms, bryozoans, and tunicates were among the dominant organisms

inventoried. The number of colonizing species gradually increased to about seven or eight species after eight months (February) and remained constant thereafter to the termination of the experiments (11 months). From these data it appears that initial colonization is very quick in the spring/summer, results in a community consisting of relatively few species, continues at a more subdued rate in the fall and winter and undergoes a small spurt in the following late winter/early spring. The equilibrium points were reached in 3 to 9 months. On panels that were deployed for just one month, most recruitment occurred in April through September, with very little to no recruitment in November through March.

It should be noted, however, that this study involved organisms most likely to colonize a continually submerged substrate. As a result, the flora and fauna were more typical of an Alaskan subtidal environment that is constantly emersed, instead of the intertidal portions of beaches most susceptible to impacts from a rock washing operation.

5. The TORREY CANYON Spill/Dispersant Treatment

The unique characteristic of this spill was the widespread use of oil dispersants. The spill consisted of 14,000 tons of Kuwaiti crude oil which was stranded along 150 km of the coast of West Cornwall, England in March 1967. The oil was treated with 10,000 tons of toxic dispersants during the cleaning operations. A combination of oil and dispersants killed off most animals and plants in heavily treated areas, but in less treated areas, some of the organisms survived. This produced a situation analogous to the results of rock washing, since it is presumed that rock washing would destroy the organisms that exist on and around the beach material being treated. However, in the TORREY CANYON spill, residues of dispersants remained after cleanup, and a slower rate of recolonization in certain areas was attributed to them. Moreover, most of the sites in this study consisted of rocky shores rather than the unconsolidated beaches characteristic of the candidate sites in Prince William Sound.

The definition of recovery in this study was related to three aspects: (1) comparison with other areas not affected by oil or dispersants, (2) species richness, and (3) the wide range of sizes and age groups of the organisms being inventoried.

Studies of the process of recolonization were an important part of the research occurring because of the TORREY CANYON spill. As a result of this research a greater understanding was gained of the colonization sequence that occurs when a natural marine site is profoundly disturbed. Following the oil spill and the indiscriminate use of dispersants, the sequence of colonization events were found to be:

- (1) delayed settlement of organisms
- (2) appearance of diatoms and filamentous algae
- (3) rapid greening by *Enteromorpha*
- (4) *Fucus* growth and die-off of barnacles
- (5) settlement of limpets and other grazers
- (6) loss of brown algae
- (7) reduction in abundance of limpets and resettlement of barnacles
- (8) the return of limpets and barnacles.

When the dominant *Fucus* growth was not heavy, the entire sequence took approximately five to eight years. When *Fucus* was a more prevalent component of the intertidal flora, the process was completed in approximately nine to ten years.

It was also found that some species may disappear completely from the intertidal communities in which they had existed prior to such disasters. This was the case with one species of hermit crab in a particular region impacted by this spill and the ensuing cleanup (Southward and Southward, 1978).

6. Lake Huron Beach Nourishment

In this project, beach material (cobble/gravel/coarse sand) was removed from one beach and added to another nearby beach in Lake Huron (Nester and Poe, 1982). The excavation and augmentation took place in October 1980. Samples were analyzed for biological community composition before and after the project. The abundance of oligochaete worms and chironomid insect larvae in shallow nearshore samples collected in June 1981, eight months after the project, was not significantly different from the abundance of these groups in the June 1980, sampling period before the project. The data suggest that biological recovery by these two groups was

complete within eight months. It should be pointed out that the death of the organisms was most likely caused by the grinding and crushing of the beach materials on the organisms, rather than a chemical alteration. Some species may have survived the transport ordeal and initiated the recolonization processes in the new beach locations.

7. Puget Sound Colonization Curves

Colonization curves were determined for artificial substrates (panels) that were deployed in different sites in Puget Sound (Schoener, 1983). Some sites were known to be relatively highly contaminated with toxic chemicals and others were known to be relatively clean. Replicate clean substrates were deployed near the bottom at each site and colonization was monitored monthly for 18 months using a non-destructive approach. The colonization curves for the contaminated and clean sites differed. At the clean sites, the equilibrium points consisting of about 18 to 22 species, and were reached within about seven months. At the contaminated sites, equilibrium points of about 14 to 16 species were reached within seven months. Within 18 months, the numbers of species at all sites were similar (about 15 species) and the distinction between clean and contaminated sites disappeared. From this study, it appears that some initial delay in colonization of hard surfaces, such as boulders, would be expected if toxicants remained in the environment as compared to relatively clean environments.

8. AMOCO CADIZ Oil Spill 1978/Beach Treatment

In 1978, the AMOCO CADIZ spilled 223,000 metric tons of light Arabian and light Iranian crude oil, and 2,000 tons of Bunker C oil off the coast of Brittany, France. Large scale clean-up operations took place in most localities, using booms, tractors, honey wagons, front-end loaders, high pressure flushing, movement of oiled gravel/cobble into the surf zone, and hot water wands. The ~~kind~~ of shorelines affected included bedrock headlands, sandy beaches, mud estuaries, seagrass beds, mixed sand and gravel and cobble beaches, and marshes. Some of the sites are similar to the Alaska rock washing sites. The Brittany coast resembles the coasts of Washington and Oregon in climate, and is similar to portions of the Alaskan coast in wave action and tides. Information from several sources is compiled here and will be related as closely as possible to the Prince

William Sound spill situation. The oil has persisted for a long period of time, and still may be found on the beach in some areas.

There were multiple definitions of recovery for this spill. These included: the return of populations to normal densities; the absence of reproductive pathologies and fin necroses in fish; normal catch numbers of commercially important species (crabs, lobsters, fish, etc.); decline of mortality rates and levels of hydrocarbons in the tissues of certain key species to low or acceptable levels; and the return of species thought to have disappeared due to the oil/cleanup impact (amphipods and copepods, and clams). Equilibrium of the communities was a final measure of recovery in these habitats (Marshall and Gundlach, 1990).

On gravel/cobble beaches, it was reported that the oil was removed by a combination of clean-up procedures and natural processes within 1 to 1.5 years after the spill. Certain beaches were impacted again by another spill, the TANIO (7 March 1980), which obviously complicated assessment of recovery. With that spill, recovery occurred within approximately one to two years for plants (Gundlach et al., 1981), and within one to three years for animals (Gundlach et al., 1983). Finfish returned to normal population densities in one year, and flatfish in three years, showing no pathologies in reproduction and fin necroses. Crabs returned in one year, oysters in one to three years, and the plants *Laminaria*, *Fucus*, and *Ascophyllum* in one to two years after the spill. The chronologic sequence (Glemarec and Husenot, 1982) leading to equilibrium covered three years, but certain imbalances and perturbances persisted longer (Bodin and Boucher, 1982).

9. TAMANO Oil Spill and Treatment, Casco Bay, Maine, 1972

On 22 July 1972, the TAMANO spilled 100,00 gallons of No. 6 fuel oil at the entrance of Casco Bay, Maine. The areas shoreline included steep rock shelves, outcrops, and intrusions. This area is a major recreational site, and significant amounts of seafood (lobsters, shellfish, and seaweeds) are harvested from its waters.

Seaweed beds were cropped, but holdfasts were left and hot water under pressure was used to clean rocks. Booms were used to contain oil and sorbents picked up refloated oil. Oil penetrated the beaches into the underlying sand.

Comparisons between oiled and unoled sites were studied one year after the spill to determine the effects of the contamination and recovery. Intertidal mudflat fauna were completely lost at one site, and contamination of clams and sediments were recorded at less affected areas. Seaweeds, barnacles, and snails were killed and lobsters showed increased hydrocarbon burdens. One year later, the sites were studied again and it was found that mudflats showed no evidence of new recruits. In contrast, new sets of shellfish did occur at control sites. Seaweeds did best where oiled fronds had not been removed, but still were in reduced abundance in cropped areas. Hot water cleaned areas were slower to recolonize, but in the lower intertidal rock surfaces and tidal pools, life was more diverse (Marshall and Gundlach, 1990).

10. AMAZZONE Oil Spill/Hot Water Washing. Brittany. 1988

About 1,500 tons of paraffinic medium fuel oil from the AMAZZONE impacted the coast. The beaches that were of greatest concern were the cobble/pebble types. A large-scale washing plant was moved in for testing, which consisted of water washes of varying temperatures with the use of petroleum cut and surfactants. The Brittany coast is much like the coasts of Washington and Oregon in climate, and like Alaska in wave action and tides. The kind of beach material along this coast includes bedrock headlands, sandy beaches, mud estuaries, seagrass beds, mixed sand/gravel/cobble beaches, and marshes. Some of the sites were similar to the candidate Alaska rock washing sites.

Although equipment limitations restricted the highest water temperature to 17°C, the results of the washing tests indicated that higher temperatures were better than lower temperatures in oil removal. However, the oil was still present on the pebbles even though the efficacy of the cleaning technique was rated good. It was concluded that modifications of technology were needed (Marshall and Gundlach, 1990).

11. Restoration of Intertidal Beach Habitat near Stanley Park, Vancouver, B.C.

Under the direction of Dr. Jeff Marliave of the Vancouver Aquarium, a portion of the intertidal shoreline near Stanley Park in Vancouver, B.C. was reconstructed to correct a problem with siltation that had effectively

eliminated natural spawning habitat for sculpins and blennies. Observed results of the rehabilitation project were summarized in Sea Pen (1990), with discussions in scientific literature in preparation.

Over 70 tons of rock and gravel were carefully placed on the beach to approximate preexisting and preferred habitat. A section of shoreline 10 meters wide was restored. Fish, shrimp, and crab were observed to move into the new habitat, and wintertime low-tide surveys indicated that the restored area was being utilized by cockscomb prickleback (*Anoplarchus purpureus*) and crescent gunnel (*Pholis laeta*) for spawning. The padded sculpin (*Artedius fenestralis*) also commonly spawned at the site. Comparisons to observations made by Marliave prior to the episode of siltation showed that the spawning populations included both the same species that had previously used the area, as well as related but new species.

While demonstrating the feasibility of habitat restoration in the intertidal zone, the Stanley Park project also demonstrated the necessity for careful placement of substrate during beach rehabilitation. A federally mandated mitigation project in outer Vancouver Harbor that emphasized substrate selection and placement to a much lesser degree than Marliave's project was monitored as part of the latter, and failed to show any fish reproduction at all despite its location adjacent to spawning areas.



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
OFFICE OF OCEANOGRAPHY AND MARINE ASSESSMENT
OCEAN ASSESSMENTS DIVISION
Hazardous Material Response Branch
7800 Sand Point Way N.E. - Bldg C18700
Seattle, Washington 98116

March 15, 1991

RADM David E. Clancaglini
Cdr (d)
Seventeenth Coast Guard District
P.O. Box 3-5000
Juneau, Alaska 99802

Dear Admiral Clancaglini:

Enclosed is a summary of NOAA's review of the status of Prince William Sound shorelines following two years of treatment by Exxon.

Sincerely,

David M. Kennedy, Manager
Spill Response Program

Enclosure



INTRODUCTION

As the Exxon Valdez oil spill shoreline treatment program enters a third year, special attention must be paid to the development of a cleanup strategy that focused on finding a balance between any benefits that may be derived by removing oil and the potential for compounding the injury to the environment through the use of increasingly intrusive treatment methods. We are rapidly reaching the point of diminishing returns where the amount of effort, and the associated impact required to further reduce the total amount of oil remaining on, or in, a beach can not be justified based solely on the assumption that the presence of oil poses a threat to the overall health of the local environment.

This paper will review the status of recovery of those areas impacted by the Exxon Valdez oil spill, discuss the potential threat to the environment posed by leaving oil on the beaches and examine the advantages and disadvantages of the various treatment options being considered for use in 1991. This paper does not address socioeconomic concerns or issues involving specially threatened species.

SHORELINE STATUS

Oil Characteristics

Weathering (natural and enhanced) continues to change the physical and chemical characteristics of the oil remaining on the shoreline of Prince William Sound and in the Gulf of Alaska. Although there is extensive variability, the shoreline oil can be characterized into four general types, based on appearance, location, and chemical composition. NOAA has developed an extensive database on the chemical characteristics of stranded oil as a function of time, upon which these generalizations are based.

1. Surface oil which occurs as cover/coat/stain on rock surfaces and gravel. This oil type is heavily weathered, it represents a very small volume of oil, and it is not readily mobilized. The oil will continue to weather to a black, inert material with little to no environmental risk.
2. Surface oil which occurs as asphalt pavements. This oil type is heavily weathered on the exterior, but may encapsulate less weathered oil within. Remaining pavements are expected to be relatively small in size and have scattered distributions. This category would also include surface oil residue. They are easy to remove, can have high concentrations of oil relative to the volume of material to be removed, and can impact habitats, if only by physically changing it.
3. Surface oil which occurs as mousse, tarballs, or tar patties. This oil type is most commonly found as soft, relatively thick oil in crevices, and in "underrock" and sheltered rocky environments. This oil has very limited potential for being mobilized unless it is physically disturbed (i.e., during cleanup or intense storms). Even the thicker deposits have weathered

significantly. If left in place, this material will continue to weather to form hard tar deposit.

4. Subsurface oil which remains in permeable beaches below the depth of sediment reworking. Although limited in areal extent, the concentrations of residual oil can be high, and subsurface samples show the slowest rates of both physical and chemical weathering. Even the deposits with high concentrations show extensive loss of the more toxic aromatic compounds. In most places, the surface sediments are clean, having been reworked during two storm seasons. The oil would be exposed primarily during future, more intense storms, which would disperse the oil over large areas.

As an example of subsurface oil, Figure 1 shows plots of the relative abundance of polynuclear aromatic hydrocarbons (PAHs) in the fresh oil and two subsurface samples collected over time from the middle intertidal zone of Smith Island. The chemical composition of the oil is highly variable, but the Smith Island samples represent worst-case examples of the amounts and types of subsurface oil present. The September 1989 sample contained total petroleum hydrocarbons (TPH) at about 40,000 mg/kg, and the January 1991 sample contained about 18,000 mg/kg, so both samples represent relatively high degrees of oiling. On the left-hand side, the PAHs are plotted normalized to C-1 chrysene, which is one of the more resistant compounds; on the right, the two samples are plotted relative to the highest peak for each sample to better show internal changes in the relative amount of components. It should be noted that the PAHs represent about 1 percent of the fresh oil, but they are the source of nearly all of the acute and chronic toxicity associated with the oil.

The normalized plots show that, as of September 1989, weathering had removed the light molecular weight PAHs (e.g., benzene) and some of the middle molecular weight PAHs (e.g., naphthalenes). Note that there was little change in the high molecular weight compounds, from phenanthrene and higher. However, by January 1991, the total amount of PAHs had been significantly reduced, even though the TPH levels were about 18,000 mg/kg. Of the remaining PAHs, there have been losses of the lighter members of a series, that is, a steady loss of the C-1, C-2, and C-3 naphthalenes relative to the C-4 naphthalenes, as shown in the non-normalized plots in Figure 1. The bulk composition of the remaining oil is comprised primarily of the residual or asphaltene fractions which have negligible water solubility and little demonstrated toxicity, and thus pose little environmental risk to intertidal and water-column organisms, even if there were routine releases.

Recovery of Intertidal Organisms

In 1990, NOAA began a study to determine the extent of biological recovery of the intertidal communities in Prince William Sound. The study also included a review of the treatment records for 24 sites to evaluate the impacts of various treatment methods on the recovery process. The parameters monitored to measure the extent of recovery included community diversity, the presence (or absence) of recruitment, and population growth characteristics for several species.

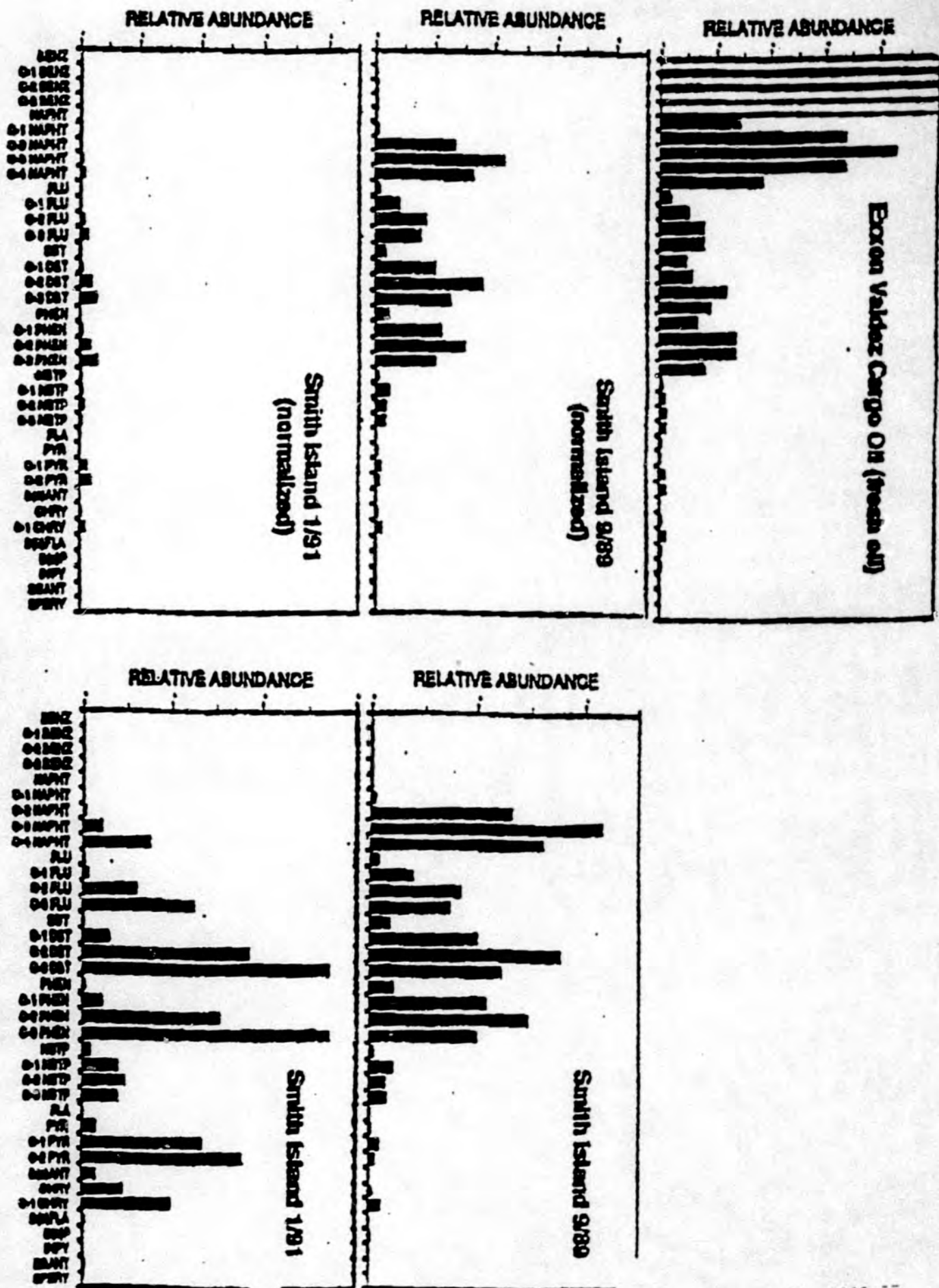


Figure 1.

These histograms show the relative distribution of polycyclic aromatic hydrocarbons in the original Exxon Valdez cargo oil (upper left) and samples of subsurface sediments from the mid-tide level at Smith Island. The two plots on the left are normalized to C-1 abundance. The two plots on the right are normalized to C-1 abundance.

Initial results from this study corroborate anecdotal observations and strong support the hypothesis that the process of recovery is well underway on the shorelines that were oiled by the *Exxon Valdez* spill. The results also suggest that some of the differences in the apparent rates of recovery among oiled beaches may be a result of the use of intrusive treatment methods and not simply related to the degree of initial oiling.

Chemistry/Toxicology

Although a potential exists for continuing impacts on the biological community due to the toxicity of oil remaining on the surface or buried in a beach, this risk appears to be a minor one. The more toxic, and more soluble, fractions of the oil are no longer present, even in the "freshest-appearing" oil found in some persistent subsurface pockets. The remaining surface oil has been weathered, and treated, for two years and, with few exceptions, has lost most of the components that are known to be acutely or chronically toxic. When the toxicity of the remaining oil is addressed by attempting to establish potential routes of exposure and candidate target organisms, the appropriate levels of concern become quite clear. The oil that remains buried after two winter storm seasons is not mobile and the likelihood of a release is small. This oil, therefore, does not present a significant hazard to terrestrial or aquatic organisms as it is not readily available to them. Future releases of this buried oil would only occur during a major storm event, and the mechanical washing due to high energy wave action during such an event would rapidly disperse any oil that was released.

The NOAA monitoring program indicates that, even where there is direct contact with weathered oil, intertidal organisms have shown extensive recovery. Detailed studies at 24 sites in Prince William Sound under the NOAA monitoring program showed that species were just as diverse at unoiled sites as at oiled but untreated or lightly treated sites. Of greater concern, perhaps, is the potential for incorporation of PAHs from residual oil into the food chain, resulting in sublethal effects. Again, the NOAA monitoring program attempted to evaluate this potential through analysis of PAHs in intertidal organisms at different trophic levels: periwinkle snails, which are herbivores grazing on algae; mussels, which are ubiquitous filter feeders; predatory drills, which feed on mussels and barnacles; and seastars, which are voracious predators who feed on bivalves. The results showed some accumulation of PAHs, but no evidence of biomagnification up through trophic levels of the food web: the highest tissue concentrations of PAHs were found in intertidal mussels, the filter feeders, but mussel predators had much lower tissue levels. These intertidal communities represent the worst-case exposure conditions since they are directly exposed to sheens and interstitial water that constitute much greater amounts of oil than water-column exposures.

SPECIFIC CONCERNS

Subsistence Harvest Areas

The Exxon Valdez spill caused the residents of many of the villages in Priz William Sound, Lower Cook Inlet, and Kodiak Island to become concerned about potential contamination of traditionally harvested finfish and shellfish resources. A subsistence food sampling program conducted during the summers of 1989 and 1990 examined impacts to these resources in designated subsistence harvest areas that were thought to be affected by the spill. Based on the results of chemical analyses of tissue samples collected during this study and on demonstrated patterns of subsistence seafood consumption from representative villages, the Quantitative Risk Assessment Committee of the U.S. Food and Drug Administration estimates that the risk associated with the consumption of even the most substantially contaminated subsistence fish and shellfish was low. This assessment should be considered conservative, as the majority of samples analyzed contained detectable levels of hydrocarbons that could not be statistically differentiated from background levels found in the control samples.

Based on the results of these studies, subsistence harvesting areas should not be singled out for treatment simply because they represent a source for subsistence foods. The sites should, however, be candidates for avoiding treatments that could either release oil into subsistence harvesting areas or add materials to the beach which will raise more concerns as to the potential for contamination through treatment products (bioremediation, beach cleaners, etc.).

Anadromous Streams

Oil remaining in the banks of a number of anadromous fish streams remains of concern because of the potential for future releases during stream migration. Mechanical tilling or extensive altering of a stream bed is not recommended, for several reasons. The residual oil has very low toxicity; monitoring of eggs and larvae in oiled streams has shown significant reductions in effects in 1990 versus 1989. The stream bed itself is a relatively high-energy environment, and stream migration occurs during high-flow conditions which would tend to flush the system of oil and oiled sediments. Previous efforts in mechanical stream cleanup have been shown to be difficult and result in extensive disruption of the stream habitat. The results of the 1991 shoreline survey of anadromous streams need to be very carefully evaluated so that the cleanup activities are appropriate to the environmental risk.

TREATMENT RECOMMENDATIONS

OILING CHARACTERISTICS - SURFACE

Cover, Coat, and Stain

Description

This is surface oil which occurs as a thin deposit on bedrock and individual clasts. The thickness of the deposit determines whether it is classified as coat ($> 1\text{mm}$), cover ($< 1\text{mm}$ but can be scrapped off), or stain (cannot be scrapped off). It can range from dry and black to soft and brown. On bedrock, it most frequently occurs on the sides of outcrops in the mid- to upper intertidal zones. Thick deposits show evidence of removal by flaking. On clasts, it occurs mostly as stain, except for those areas where berm relocation was conducted in 1990.

Environmental Concerns

Heavy residual oil coatings can affect the value and utilization of bedrock surfaces. However, as the oil continues to weather, these impacts are expected to decrease. Healthy populations of mussels and snails are utilizing surfaces with a heavy coat of weathered oil. Any efforts to remove the oil will only result in greater impacts to the intertidal communities.

Treatment Recommendation

No treatment is recommended.

Asphalt Pavements/Tarmats

Description

Asphalt pavements and tarmats are heavily oiled sediments, which form a coherent surface deposit. They occur most frequently in the upper intertidal zone. There is usually a weathered surface skin and soft-to-hard oiled sediments within. Remaining pavements are thought to be small in size and scattered in distribution. They are readily removed by manual methods.

Environmental Concerns

Asphalts pavements and tarmats will eventually harden into resistant oil deposits. The principal concern is that they immobilize the sediments and thus affect habitats. They also will weather very slowly.

Treatment Recommendation

Manual removal is recommended for readily accessible pavements and tarmats. Those deposits which can not be removed manually (i.e., those requiring mechanical assistance) should be left in place. Only surface deposits should be removed.

Mousse/Pooled Oil

Description

Mousse patties and pooled oil are surface deposits of soft, relatively thick oil, mostly in rock crevices, at the base of large boulders, and below a surface veneer of coarse, rocky rubble. It can occur as scattered individual patties or a

discontinuous band. These deposits readily sheen when disturbed. Because they are mostly emulsified oil, they are expected to weather very slowly.

Environmental Concerns

Where thick mousse/pooled oil occurs in "underrock" environments, it may affect sensitive infauna. The scattered individual patties are less of an environmental risk.

Treatment Recommendation

Manual removal for accessible mousse and pooled oil. Spot washing (high pressure, hot water) can be used to mechanically break apart inaccessible mousse or pooled oil in order to increase the surface-to-volume ratio and promote biodegradation.

Tarballs/Tar Patties

Description

Tarballs and tar patties are individual deposits of oiled sediments which are less than 10cm in size. They are mostly friable to hard, but may soften under warm, sunny conditions to the point that they assume the physical appearance of mousse. They are mostly widely scattered in the Kenai and Kodiak regions.

Environmental Concerns

Tarballs and tar patties do not present a significant environmental threat because they are immobile, small in size, and very widely scattered. They contain highly weathered oil with little likelihood of a pathway of exposure to sensitive resources.

Treatment Recommendation

Where cleanup activities are already scheduled, tarballs and tar patties should be manually removed. Otherwise, no treatment is recommended.

Surface Oil Residue

Description

Where previous treatment activities removed surface deposits, the underlying material which was not removed is described as a surface oil residue. The nature and distribution of this residue is highly variable depending on the original type of oil and the efficacy of its removal. It mostly occurs in very sheltered environments which were initially heavily oiled.

Environmental Concerns

This oil will be highly weathered with little toxicity. However, there can be locally thick deposits which could physically affect the immediate habitat.

Treatment Recommendation

Heavy accumulations of surface oil residue could be scraped from rocks. Otherwise, no treatment is recommended.

OILING CHARACTERISTICS - SUBSURFACE

Oil Film/Light Oil Residue

Description

Where subsurface sediments are coated with an oil film, it is described as C. If there is only a trace of visible brown/black oil, it is described as light O. Frequently, the only indication of the presence of oil are light sheens on the water table in trenches.

Environmental Concerns

The oil is highly weathered and most amenable to degradation. The very low concentrations do not pose any significant environmental concern.

Treatment Recommendation

No treatment is recommended.

Medium Oil Residue

Description

Where individual subsurface sediments are coated brown/black but the pores are not saturated with oil, it is described as medium OR. This oil type is found mostly in gravel beaches, in the mid- and upper intertidal zone. Although it can extend to the surface, it most commonly occurs below a layer of clean sediments.

Environmental Concerns

Where it occurs below a layer of clean sediments, subsurface oil will be mobilized only during significant storm activity, when the released oil will be widely dispersed. Thus, the pathway of exposure of the oil to sensitive resources is not likely to result in significant environmental risk. The subsurface oil has undergone extensive weathering as well.

Treatment Recommendation

Continuous oiling, surface to subsurface should be tilled, where practical, and then treated with bioremediation. Tilling is useful in the upper (near surface) layer only and is practically limited to a depth of approximately 40cm. Any efforts to till to a depth in excess of 40cm should be discouraged. Subsurface oil underlying a clean surface layer should be left in place. At these sites, application of Customblen™ fertilizer may be considered in mid-summer when background levels of nutrients have dropped, and no intertidal populations are present.

Pooled Oil/High Oil Residue

Description

Where the individual subsurface sediments are heavily coated with oil, or the pore spaces are saturated with oil, it is described as heavy OR or pooled oil. This oil type is found mostly in gravel beaches, in the mid- and upper intertidal zone. Although it can extend to the surface, it most commonly occurs below a layer of clean sediments.

Environmental Concerns

Where it occurs below a layer of clean sediments, subsurface oil is mobilized only during significant storm activity, when the released oil is widely dispersed. Thus, the pathway of exposure of the oil to sea resources is not likely to result in significant environmental risk. Even the heaviest subsurface oil has undergone extensive weathering of the high molecular weight PAHs.

Treatment Recommendation

Continuous oiling, surface to subsurface should be tilled, where practical, then treated with bioremediation. Tilling is useful in the upper (near surface) layer only and is practically limited to a depth of approximately 40cm. Efforts to till to a depth in excess of 40cm should be discouraged. Subsurface oil underlying a clean surface layer should be left in place. At these sites application of Customblend fertilizers may be considered in mid-summer when background levels of nutrients have dropped.

TREATMENT METHODS

Manual Removal

This technique consists of the use of hand tools for the removal of oil and oil sediments. Its application in 1991 should be no different than that of 1990.

Bioremediation

Bioremediation consists of the application of fertilizers, namely Inipol™ and Customblen™, to speed the rates of natural degradation of the oil. Although the 1990 bioremediation monitoring program results are encouraging, as reported at the EPA-sponsored bioremediation workshop in Las Vegas in 1991, they also indicate that the level of natural biodegradation in Prince William Sound is high and, in many areas, statistically indistinguishable from the degradation that takes place with the assistance of bioremediation.

High nutrient levels have been observed through the early summer, indicating that Prince William Sound may not be nutrient-limited until late summer. If bioremediation is utilized, the most desirable approach may be to delay treatment until late July or early August.

Considering these comments, bioremediation is recommended only in conjunction with some other treatment that may disrupt the "natural" or unassisted process. If aggressive treatment is warranted, then the added intrusion of bioremediation may help speed degradation in the treated area. However, if a site is not scheduled to be disturbed manually or mechanically, then use of bioremediation is not justified. The only exception might be on gravel beaches with heavy oil residue in the subsurface. Application of Customblen™ may be of value in mid-summer.

Spot Washing

This technique consists of the use of small, portable, hot-water units and hand wands to produce a high-pressure, hot-water spray. The oil is removed primarily by the high-pressure spray, with the hot water used to soften the oil and sorbents placed at the base of the work area to catch any oil which is released. Attached organisms will also be removed and those infauna exposed to hot water in the immediate treatment area would likely die; therefore, this technique should not be used in areas with any significant amount of epifauna.

Tilling

Tilling consists of the use of mechanical equipment to break up and mix the upper 40cm or so of sediments on gravel beaches. Large boulders have to be displaced before tilling can be done. Tilling may include physical displacement of the sediments to a different location on the beach. The objectives of tilling include: 1) physically breaking up the oiled sediments, particularly where heavy oil has apparently acted as a cement and restricted sediment mobilization, 2) increasing the surface area of the oil relative to its volume by mixing, and 3) redistributing heavy subsurface oil, bringing it closer to the surface for natural removal by sediment reworking during storms.

UNITED STATES DEPARTMENT OF
COMMERCE
NEWS

WASHINGTON, D.C. 20230

NATIONAL
OCEANIC AND
ATMOSPHERIC
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NOAA Says Efforts to Clean Alaskan
Shoreline May Have Backfired

FOR IMMEDIATE RELEASE

NOAA (the National Oceanic and Atmospheric Administration) reported today that, among techniques employed to remove oil from Alaska's beaches after the 1989 Exxon Valdez oilspill, the use of hot water under high pressure may have done more environmental harm than good and should be avoided in the future.

"Sometimes the best, and ironically the most difficult, thing to do in the face of an ecological disaster is to do nothing," said Dr. Sylvia Earle, NOAA's Chief Scientist.

"Certainly, as far as Alaska's shoreline is concerned, the environment would have been better off if there had been less aggressive hot-water treatment and we had let nature take its course," Dr. Earle said.

The cleanup, involving thousands of man-hours and millions of dollars' worth of equipment, began shortly after the Exxon Valdez spilled 10.8 million gallons of crude oil into Alaska's Prince William Sound.

Typically sea water, as hot as 150 degrees F. and pumped from hoses at pressures up to 100 pounds per square inch, was used to wash sticky oil from an estimated 400 miles of Alaska's shoreline. The oil that washed into the water was then collected and pumped into onshore storage tanks.

According to the NOAA study, which compared species diversity and abundance among oiled, oil-treated, and oil-untreated sites, the high-pressure hot water displaced oil from upper to lower parts of the beach and into tidal pools where it damaged a wide variety of marine plants and animals.

The study says the hot water in effect sterilized many parts of the beaches, reducing both the number and diversity of marine life, including barnacles, mussels, clams, eelgrass and rockweed.

In addition according to the study, the high-pressure treatment, regardless of water temperature, greatly altered the physical aspect of the beaches, flushing finer sands and gravel from upper elevations down the beach slope, often burying the lower beach in several inches of oily sediment.

more

By contrast, oiled but untreated sand and gravel beaches had richer and more varied marine life, similar in most instances to sites where no oil had come ashore.

Charles H. Ehler, head of NOAA's Office of Oceanography and Marine Assessment charged with tracking oil spills, said that with proper planning and prepositioning of technical equipment, the amount of oil that comes ashore -- and therefore problems of cleanup -- can be substantially reduced.

The study, conducted for NOAA by Pentec Environmental, Inc., of Edmunds, Wash., and Environmental and Energy Service Co., of San Diego, was based on examination and analysis of 24 sites in Alaska during the summer of 1990.

The study was paid for by NOAA, the American Petroleum Institute, the Coast Guard and the Environmental Protection Agency.

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4/9/91

2

Exxon Valdez Shoreline Monitoring Program: 1990 Results

GENERAL

- ☐ Program goals: To assess recovery of intertidal and subtidal marine communities impacted by the Exxon Valdez oil spill and cleanup, and to evaluate differences in recovery among areas subjected to different treatment methods
- ☐ Sponsored by NOAA Administrator's Office, American Petroleum Institute, U.S. Coast Guard, and U.S. Environmental Protection Agency; vessel and aircraft logistics provided by Exxon U.S.A.
- ☐ Twenty four sites located in Prince William Sound, with shoreline types ranging from rocky to muddy, degree of oiling from unoiled to heavily oiled, and shoreline treatment from untreated to intrusively treated
- ☐ Primary focus for assessment of treatment impacts: high pressure, hot water washing

RESULTS

- ☐ Evidence of intertidal recovery was observed at all impacted sites
- ☐ Chemical analyses of tissues from selected intertidal organisms indicated accumulation of hydrocarbons from the environment but no evidence of magnification through predator-prey interactions
- ☐ Removal of oil through shoreline treatment may have improved conditions for organisms at the sediment-water interface and for eelgrass
- ☐ Flora and fauna at beaches receiving light or no shoreline treatment strongly resembled those at unoiled beaches, with some reductions in abundance at oiled beaches
- ☐ Abundances of important intertidal species such as rockweed, limpets, snails, hermits crabs, and mussels were significantly lower at beaches receiving high pressure, hot water washing
- ☐ Distribution and abundance for organisms living in cobble/gravel beaches were reduced to a greater degree by initial intrusive treatment than by remaining sediment hydrocarbon concentrations
- ☐ Full recovery to pre-spill conditions on rocky shorelines where high pressure, hot water washing reduced cover of mussels and vegetation is expected to take several years
- ☐ Long-lived, slow-reproducing organisms such as hard-shell clams may take many years to recover from effects of hydraulic burial and mortality of young clams from hot water exposure

CONCLUSIONS

- ☐ Plants and animals inhabiting Prince William Sound shorelines showed impacts from both oiling and attempts to clean up the oil. However, recovery processes at sites known to have been oiled and high pressure, hot water washed were significantly impaired relative to sites oiled and receiving lesser or no treatment

3

EXXON VALDEZ SHORELINE MONITORING PROGRAM, 1990: INTRODUCTION

1.1 GENERAL

The National Oceanic and Atmospheric Administration (NOAA) Hazardous Materials Response Branch is mandated by the National Oil and Hazardous Substances Pollution Contingency Plan as the trustee for living marine resources in the coastal zone. NOAA provides technical staff to advise the Federal On-Scene Coordinator charged with directing oil and chemical spill response and clean-up activities. NOAA uses its role as the Federal Government's emergency spill response agency both to provide advice during real-time spills and to conduct research with the goal of better protecting the marine environment from the effects of spills. In the case of the spill of 10.8 million gallons of North Slope crude oil from the tanker *Exxon Valdez*, NOAA blended its response and research roles to begin a program to address two areas of great uncertainty and misunderstanding about the effect of oil on shorelines:

- 1) The length of time required for damaged ecosystems to recover; and
- 2) The effects of treatment activities on marine life and the extent to which treatment enhances or delays recovery.

An implied working assumption related to clean-up activities is that, once stranded on the shoreline, oil in any concentration is detrimental to shoreline marine life. A further assumption is that any biological damage resulting from the treatment of stranded oil is justified by the accelerated recovery of the affected environments. Contradicting these assumptions is the consensus of most biological reviewers that shoreline treatments may well do more short-term ecological harm than good. Moreover, in most habitats, certain methods of treatment may actually delay rather than accelerate environmental recovery (Lindstedt-Siva 1979; Broman et al. 1983; Foster et al. 1990; Rolan and Gallagher 1991).

This document is a progress report on studies designed to test these assumptions for shoreline and subtidal marine life of Prince William Sound, Alaska, following the spill from the *Exxon Valdez*. It is imperative that information regarding shoreline recovery from the *Exxon Valdez* spill and the various treatments applied be made available to decision-makers before the next such incident occurs. This is the general rationale for the present

study, initiated by NOAA under contracts 50ABNC-0-00121 and 50ABNC-0-00122. Funding was provided by NOAA, the U.S. Environmental Protection Agency, the U.S. Coast Guard (USCG), and the American Petroleum Institute. Logistical support was provided by Exxon Company, USA.

1.2 DOCUMENTATION OF SPILL IMPACTS

The *Exxon Valdez* ran aground on Bligh Reef, in the northeastern part of Prince William Sound, Alaska, on March 24, 1989. Over the next several weeks, a substantial amount of the 10.8 million gallons of North Slope crude oil spilled was deposited on beaches in the southern and western portions of the Sound, as well as on Gulf of Alaska beaches to the southwest. Beach clean-up activities began in Prince William Sound in May 1989 and continued with varying degrees of intensity throughout the summer, ultimately encompassing about 560 kilometers of shoreline in the Sound (Harrison 1991). At its peak, the clean-up and support force involved over 11,000 persons and some 1400 vessels of all sizes (Carpenter et al. 1991). Additional clean-up activities were carried out during the summer of 1990 using manual and mechanical techniques, often followed by "bioremediation" (treatment of oiled areas with fertilizer).

Within days of the spill, scientists from several state and federal agencies, as well as those contracted by Exxon, began evaluating spill effects. A large body of data was gathered in 1989 that will help scientists characterize the short-term effects of the spill at numerous locations both in the Sound and along Gulf of Alaska shorelines (Maki 1991). A few weeks after the spill, however, impending legal action under the Natural Resources Damage Assessment (NRDA) procedures severely limited the free exchange of information; protracted legal proceedings may restrict the release of the data collected by Exxon and the government for several years to come. At present, the authors have located only one semi-quantitative description of the biological effects of the *Exxon Valdez* spill on shorelines in the open scientific literature. Juday and Foster (1990) provide useful general descriptions of intertidal zonation prior to and following the spill. They do not, however, discuss the potential influence of habitat differences or beach treatments on the conditions reported.

Several studies conducted shortly after the spill provided support for concern about the effects of treatment on shoreline marine life. Data from Exxon-sponsored studies of the short-term effects of two different beach cleaning methods employed in 1989 have been released. The July 1989 Omni-barge test (Maki and Houghton 1989; Houghton et al.

1990) and the Corexit 9580 test (Lees et al. 1990) provide data sets which allow us to infer the short-term effects of oiling and describe the short-term impact of hydraulic beach treatments. Both of these hot-water, high-pressure washes clearly had significant, similar impacts on intertidal assemblages.

1.2.1 The Omni-barge Test

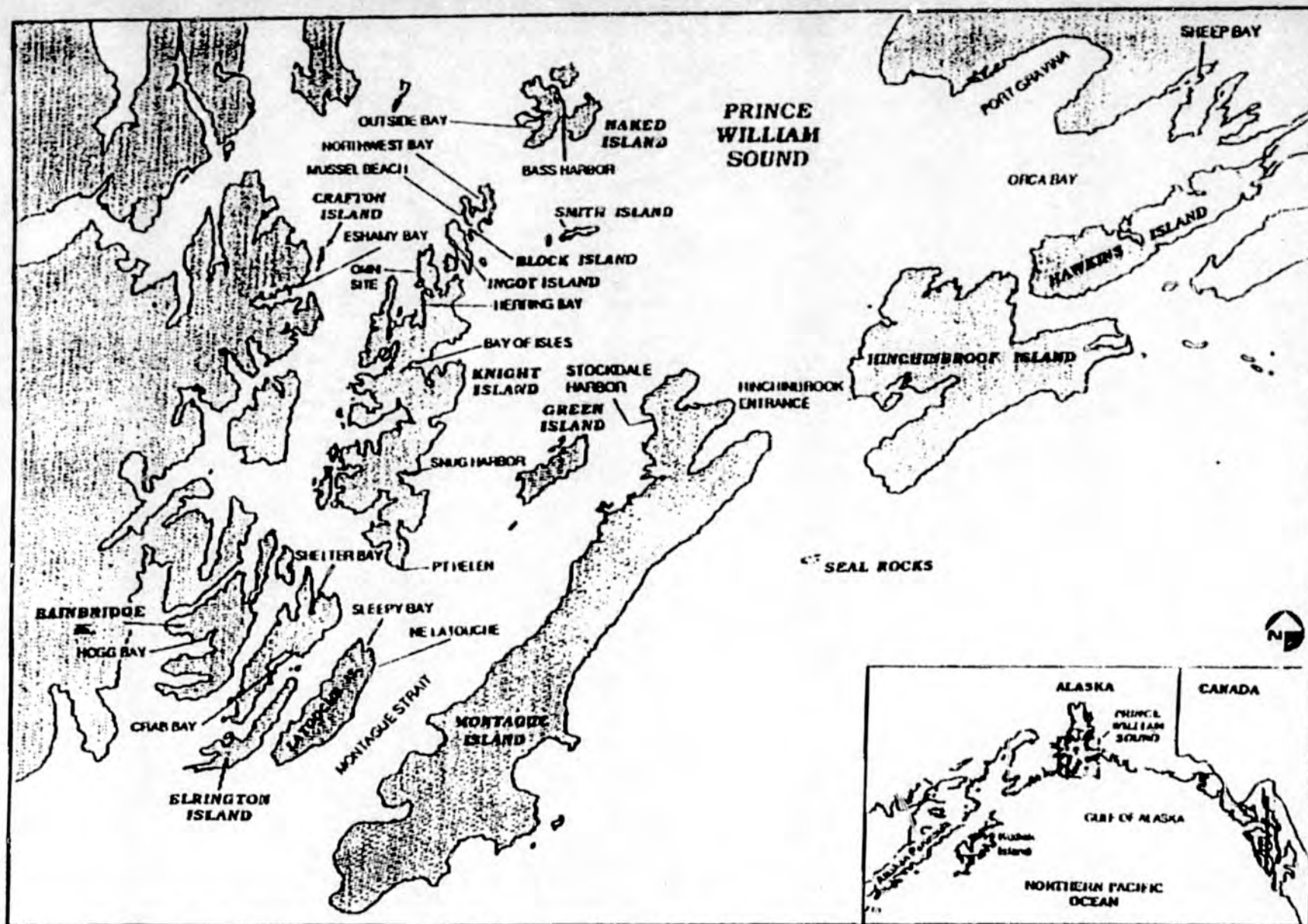
The Omni-barge was one of the several floating systems used to apply high-pressure, heated (38-60°C) water to beaches in Prince William Sound in 1989 (Nauman 1991). The Omni-barge study involved sampling two sections of a heavily oiled cobble beach on Knight Island prior to and following two different levels of treatment by an Omni-barge; one treatment lasted 165 minutes, the other 100 minutes. Sampling was conducted at two elevations on each beach section using stratified-random quadrat techniques similar to those described below.

At the time of the Omni-barge test, the study area in Herring Bay on Knight Island (Figure 1-1) had been heavily oiled and untreated for over three months. Nonetheless, the two tidal elevations sampled, in the upper and lower portions of the rockweed (*Fucus gardneri*) zone, were dominated by the same taxa reported at similar elevations on unoiled beaches in Prince William Sound (cf. Juday and Foster 1990; and data on several beaches sampled by the authors in 1990). Surviving biota included all typical functional groups (primary producers, scavengers, grazers, filter feeders, and predators).

Prior to the Omni-barge test, the upper rockweed zone was dominated by rockweed, barnacles (*Balanus/Semibalanus* spp.), and mussels (*Mytilus edulis*¹, Table 1-1). Grazers included limpets (Lottiidae) and littorine snails (*Littorina sitkana* and *L. scutulata*), although densities were somewhat lower than those found at some unoiled (control) sites in 1990 (see, for example, Table 3-4, mid-elevation sites). Small numbers of predatory snails (*Nucella* spp.) and a seastar were also present, but crustaceans were represented by a single species of hermit crab (*Pagurus hirsutiussculus*). At the lower elevation, total algal cover was much greater than at the upper elevation, as is typical for the area. Filamentous green algae, rockweed, and the red alga *Odonthalia floccosa* were the dominants (Table 1-1).

¹ The traditional "*Mytilus edulis*" designation is used throughout this report despite recent assertions that blue mussels in Alaska belong to *M. trossulus*, Gould 1850 (McDonald and Koehn 1988).





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Prince William Sound study area and sample locations

FIGURE

1-1

Table 1-1

COMPARISON OF PRE- AND POST-TREATMENT CONDITION OF INTERTIDAL BIOTA
JULY 1989 OMNI-BARGE TEST (EXTENDED WASH SITE)*

Taxon	Upper Rockweed Zone					Lower Rockweed Zone				
	Pre-wash		Post-wash		Percent Change	Pre-wash		Post-wash		Percent Change
	Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. Dev.	
<u>Plants (% cover):</u>										
<i>Cryptosiphonia woodii</i>	0.00	0.00	0.00	0.00	--	0.40	0.89	0.00	0.00	-100.0
Encrusting brown algae	0.00	0.00	0.00	0.00	--	8.60	18.21	1.30	2.28	-84.9
Encrusting coralline algae	0.00	0.00	0.00	0.00	--	0.45	0.52	0.00	0.00	-100.0
<i>Enteromorpha linza</i>	0.00	0.00	0.00	0.00	--	0.45	0.98	0.00	0.00	-100.0 **
Filamentous green algae	0.20	0.31	0.10	0.25	-50.0	48.20	35.80	26.80	24.28	-44.40 *
Flagelliform brown algae	0.00	0.00	0.00	0.00	--	0.25	0.37	0.00	0.00	-100.0 **
<i>Fucus gardneri</i>	31.27	21.50	0.31	1.10	-99.0 **	26.60	23.05	20.90	16.95	-21.4
<i>Fucus gardneri</i> (dead)	0.00	0.00	31.30	13.50	-- **					
Gigartimaceae	0.00	0.00	0.00	0.00	--	0.05	0.22	0.00	0.00	-100.0
<i>Gloiopeltis furcata</i>	0.20	0.31	0.00	0.00	-100.0	0.05	0.17	0.00	0.00	-100.0
<i>Neorhodomela larix</i>	0.00	0.00	0.00	0.00	--	0.35	1.00	0.10	0.33	-71.4
<i>Odonthalia floccosa</i>	0.00	0.00	0.10	0.25	--	18.90	11.59	19.20	11.89	1.6
<i>Palmaria callophyllodes</i>	0.00	0.00	0.00	0.00	--	0.05	0.17	0.00	0.00	-100.0
<i>Pilayella littoralis</i>	0.00	0.00	0.10	0.25	--	3.20	4.12	5.80	4.47	81.3
<i>Ralfsia</i> sp.	0.00	0.00	0.10	0.25	--	0.30	0.71	0.40	0.99	33.3
<i>Soranthra fucicola</i>	0.00	0.00	0.00	0.00	--	0.30	0.27	0.05	0.17	-83.3 **
No. of plant taxa	3.		5.		66.7	15.		8.		-46.7
Total % live cover	31.67		0.71		-97.8	108.15		74.55		-31.1

Table 1-1 (Continued)

COMPARISON OF PRE- AND POST-TREATMENT CONDITION OF INTERTIDAL BICOTA
JULY 1989 OMNI-BARGE TEST (EXTENDED WASH SITE)*

Taxon	Upper Rockweed Zone					Lower Rockweed Zone				
	Pre-wash		Post-wash		Percent Change	Pre-wash		Post-wash		Percent Change
	Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. Dev.	
<u>Animals:</u>										
<i>Balanus/Semibalanus</i> (%)	8.90	6.57	10.50	11.20	18.0	0.15	0.25	0.15	0.36	0.0
<i>Balanus/Semibalanus</i> (% set)	0.10	0.25	0.00	0.00	-100.0	0.00	0.00	0.00	0.00	--
<i>Balanus/Semibalanus</i> (dead)	2.50	2.56	0.00	0.00	-100.0 **	0.00	0.00	0.00	0.00	--
<i>Chthamalus dalli</i> (%)	0.00	0.00	0.00	0.00	--	0.05	0.17	0.00	0.00	-100.0
<i>Halichondria</i> sp. (%)	0.00	0.00	0.00	0.00	--	0.10	0.22	0.00	0.00	-100.0
<i>Lacuna</i> sp.	0.40	1.00	0.00	0.00	-100.0	0.00	0.00	0.00	0.00	--
<i>Littorina scutulata</i>	32.60	22.07	0.00	0.00	-100.0 **	11.50	37.23	0.60	1.02	-94.8
<i>Littorina sitkana</i>	22.40	15.03	0.00	0.00	-100.0 **	0.40	1.33	0.00	0.00	-100.0
Lottiidae	17.80	18.98	0.40	1.00	-97.8 **	1.00	2.98	0.60	2.00	-40.0
<i>Margarites pupillus</i>	0.00	0.00	0.00	0.00	--	0.10	0.33	0.00	0.00	-100.0
<i>Mytilus edulis</i> (%)	2.54	2.62	0.30	0.30	-88.2 *	0.20	0.37	0.20	0.37	0.0
<i>Mytilus edulis</i> (no. dead)	2.21	2.00	46.70	37.50	2013.1 **	0.70	1.32	0.10	0.33	-85.7 *
<i>Nucella lima</i>	0.60	1.00	0.00	0.00	-100.0	0.60	1.66	0.20	0.67	-66.7
<i>Nucella lima</i> (dead)	0.00	0.00	0.60	1.50	--	0.00	0.00	0.00	0.00	--
<i>Pagurus granosimanus</i>	0.00	0.00	0.00	0.00	--	0.00	0.00	0.30	0.71	--
<i>Pagurus hirsutiusculus</i>	0.00	0.00	0.80	1.46	--	19.60	16.71	13.70	9.11	-30.1
<i>Paranemertes peregrina</i>	0.00	0.00	0.00	0.00	--	0.10	0.33	0.00	0.00	-100.0
<i>Pentidotea wosnesenskii</i>	0.00	0.00	0.00	0.00	--	0.30	0.51	0.10	0.33	-66.7
<i>Pholis ornata</i>	0.00	0.00	0.00	0.00	--	0.10	0.33	0.00	0.00	-100.0
<i>Volutharpa ampullacea</i>	0.00	0.00	0.20	0.50	--	0.00	0.00	0.00	0.00	--
No. of animal taxa	7.		5.		-28.6	13.		8.		-38.5
<u>Substrate:</u>										
Boulder (%)	84.40	22.13	72.00	29.74	-14.7	61.80	26.09	59.00	31.80	-4.5
Cobble (%)	14.60	22.31	16.00	22.15	9.6	10.40	10.10	9.50	10.96	-8.7
Gravel/sand (%)	1.00	2.50	12.00	12.87	1100	20.80	20.79	24.00	23.85	15.4
Oil cover (%)	75.60	26.08	72.00	14.58	-4.8 *	44.00	36.50	21.70	32.53	-50.7
Oil scale (1-5)	5.00	0.00	2.60	1.00	-48.0 **	1.40	1.02	1.30	1.00	-7.1 *

* Significant at the 90% level

** Significant at the 95% level

Source: Maki and Houghton 1989.

Attached animals occupied relatively little primary space. The most abundant invertebrate was the hermit crab *P. hirsutiusculus*.

The two test areas were resampled approximately one week after Omni-barge treatment. In the upper rockweed zone, significant reductions ($p < 0.05$; test unspecified) in coverage of live rockweed had occurred in both the extended (165 minutes) and moderate (110 minutes) wash areas. Most remaining plants appeared to be and were recorded as dead. At the extended wash site, significant reductions had occurred in all of the community dominants (littorines, limpets, and barnacles; $p < 0.05$; Table 1-1). Percent cover of mussels dropped 88.2 percent ($p < 0.1$), while the number of dead mussels rose significantly. In the moderate wash area, similarly severe reductions were evident in littorine and limpet densities ($p < 0.05$). Live mussel cover declined significantly, unlike barnacle cover. The mean number of live animal taxa present decreased from 8 to 3.

At the lower sampling elevation in the extended wash area, the mean number of plant species dropped from 15 to 8 and total percent algae cover declined 31 percent. The latter reduction was caused primarily by a 44.4 percent ($p < 0.1$) decrease in relatively delicate filamentous green algae. The number of animal species dropped from 13 to 8, and the already low numbers of the littorine *L. scutulata* dropped 94.8 percent ($p > 0.1$). In the moderate wash area, some species reductions also occurred, but were generally less severe than in the extended wash area. Overall, the two wash durations had similar impacts on the biota.

1.2.2 The Corexit 9580 Test

The Corexit 9580 test (Lees et al. 1990), conducted at Disk Island in the Knight Island group in July 1989, evaluated a shoreline treatment approach similar to that of the Omni-barge, except that the chemical dispersant Corexit 9580 M2 was applied to one test area prior to the hot-water wash. Results in the hot-water wash area were very similar to those described in the Omni-barge test in that:

- The pre-test intertidal assemblage included all of the dominant taxa that characterize unaffected beaches in Prince William Sound; and
- The hot-water treatment resulted in significant mortalities of the dominant taxa at the upper sampling elevation and lesser impacts at the lower sampling elevation.

In addition, evidence of significant impact (75 percent mortality) to hardshelled clam populations was observed in soft sediments along the lower edge of the area treated with both hot water and Corexit (Lees et al. 1990).

1.3 SAMPLING OBJECTIVE AND APPROACH

1.3.1 Objective

The objectives of this study are to:

- Assess and compare the impacts of shoreline treatment activities (specifically: effects of hot-water washing) and oiling in important littoral (intertidal and shallow subtidal) habitats in the second summer following the spill; and
- Evaluate rates of recovery over several years in areas receiving differing levels of oiling and treatment.

Detailed information was obtained on the dynamics and ecological driving forces of recovery at a relatively small number of carefully selected sites. Data reported herein were gathered in 1990, 15 to 17 months after the initial spill. It is anticipated that similar studies in 1991, and thereafter, will provide longer-term documentation of the recovery process.

1.3.2 Approach

Our approach involved examination of a broad spectrum of features representative of conditions in: 1) a variety of intertidal assemblages and species and 2) the intertidal and shallow subtidal eelgrass populations. The intent was to produce a body of data covering many potential responses of a wide range of biological indicators to hydrocarbon contamination as well as to various disturbances caused by shoreline treatment. The data were designed to be used to compare the effects of hydrocarbon contamination and shoreline treatment and, ultimately, to compare rates and patterns of recovery in treated and untreated areas. The components examined are listed below.



INTERTIDAL

- Hydrocarbon analyses of PAHs in surficial sediments
- Quantitative epibiotic studies: abundance and relative cover
- Quantitative studies of densities of macro- and micro-infauna
- Mollusc population studies of *Mytilus edulis*, *Littorina* spp., *Nucella* spp., and hard-shelled clams: size structure, length/weight relationships, growth and mortality rates
- Hydrocarbon analyses of PAHs in intertidal invertebrates (*Mytilus edulis*, *Littorina* spp., *Nucella* spp., and *Pycnopodia helianthoides*)

SUBTIDAL EELGRASS POPULATION STUDIES

- Biomass: shoot density, shoot weight, and rhizome/root weight
- Plant condition: size structure, shoot weight/rhizome weight and shoot length/shoot weight relationships, and chlorophyll a+b
- Reproductive potential and success: abundance of flowering shoots, spadices, seeds, and young-of-year plants; seed germination success in lab experiments

Three treatment categories were defined: Category 1 (unoiled), Category 2 (untreated or moderately treated), and Category 3 (treated with high-pressure, hot-water wash). (See the Methods section for more details on assignment of categories). Based upon the stated objective, several null hypotheses were formulated to test for and evaluate effects of oiling and shoreline treatment on the intertidal and selected shallow subtidal assemblages in each specified habitat:

- 1a. Relative cover of dominant algal taxa does not differ significantly between pairs of site categories.

- 1b. Abundance (density/percent cover) of dominant species of epifauna does not differ significantly between pairs of site categories.
- 2a. Number and diversity of infaunal taxa in mixed-soft substrates do not differ significantly between pairs of site categories.
- 2b. Density of selected invertebrate species in mixed-soft substrates does not differ significantly between pairs of site categories.
- 3. Size structure and growth and mortality rates for selected mollusc populations (blue mussels, periwinkles, and drills) representing a range of feeding guilds (filter feeder, grazer, and predator, respectively) do not differ significantly among Category 1, 2, and 3 sites according to statistical comparisons of size structure.
- 4. Population characteristics of eelgrass in intertidal and shallow subtidal mixed-soft substrates do not differ significantly among unoiled (Category 1) and oiled (Category 2 and 3) sites on the basis of biomass, condition, and reproductive potential and success measures.

1.3.3 Study Area

Prince William Sound is a protected fjord system located on the southcentral coast of Alaska (Figure 1-1). Wave action from north Pacific storms is blocked by the outer ring of islands. The winds, however, are hardly abated by the low-lying peaks of those islands. This generates storm seas and chop that strike exposed shorelines with high intensity wave action during storm events. Within embayments, wave energy may be minimal despite high wind forces because of limited fetch and frequent shifts in wind direction (Bascom 1964). Tides are of the mixed semi-diurnal type, with a mean tide level of about 1.8 m and an extreme range of over 5 m.

The study area encompassed most of central and southern Prince William Sound from Sheep Bay on the eastern mainland to Eshamy Bay on the western mainland (Figure 1-1). The main sampling focus was, however, along the chain of islands stretching from Naked Island (in the central sound), south-southwest throughout the Knight Island group, to the islands protecting the southwest entrances to the sound. This portion of the sound lay in

(13)

the path of movement of oil from the *Exxon Valdez* and many beaches in these islands received heavy oiling.

1.4 GENERAL DESCRIPTION OF INTERTIDAL COMMUNITIES IN PRINCE WILLIAM SOUND

Un-oiled beaches in Prince William Sound support biological communities that are relatively specific to and characteristic of a given habitat type and range of tidal elevation. Most beaches common to the sound have uppermost zones (above mean high water, MHW) that are typically devoid of significant attached macrobiota. Biota in these zones is subject to a great deal of stress due to infrequent salt water inundation, high freshwater exposure (during periods of rain), and extremes of temperature. An exception to the generally low biological productivity of this zone occurs on upper elevations of low-energy, silty gravel or sand beaches, where salt marsh plants (including grasses, sedges, and forbs), flourish.

At somewhat lower elevations, rocky substrates are dominated by barnacles (several species) and rockweed, with abundant littorine snails and limpets (*Lottiidae*) in and under the algal canopy. This level is referred to as the "upper *Fucus* zone." Bay mussels are usually present. At lower tide levels, in the vicinity of mean lower low water (MLLW), predators such as snails (*Nucella lima*, *N. lamellosa*, and *Searlesia dira*) and starfish (*Leptasterias* sp., *Derasterias*, *Evasterias troschelii*, and *Pisaster ochraceus*) reduce grazer populations, resulting in a rich growth of algae (including rockweed, filamentous greens, and several types of red algae). This area is referred to as the "lower *Fucus* zone."

Boulder/cobble beaches have many of the same species as the rocky area but have an added component of under-rock fauna, including shore crabs (*Hemigrapsus oregonensis*), hermit crabs (*Pagurus* spp.), and other small crustaceans, along with sea urchins (*Strongylocentronus droebachiensis*), snails, burrowing anemones (*Anthopleura artemisia*), polychaetes, and several species of eel-like fish (*Pholidae*, *Stichaeidae*). In low cobbles (e.g., below MLLW), larger kelps (*Laminaria* spp. and *Alaria* spp.) and several red algae become increasingly abundant. This community may be greatly reduced on cobble beaches exposed to high wave action, as this results in movement of substrate materials.

Soft intertidal habitats in Prince William Sound include relatively steep gravel, but more typically comprise a mixture of sand, gravel, shell, and some cobbles, with finer materials according to the energy regime (increasing silt with decreasing wave/current action). The

upper portions of "mixed-soft" intertidal substrates often have enough gravel or cobble to support the same primary species as the upper portions of rock and cobble beaches. Rockweed, barnacles, littorines, mussels, and limpets are the numerical dominants.

Epibiota at lower elevations is also dependent on the presence of hard substrates (such as gravel and cobbles) for attachment. Lower portions of soft beaches typically support a number of clam species (butter clams, littlenecks, and others), as well as naticid snails and sea stars, both of which feed on these clams. Additional infauna in the lower intertidal and subtidal eelgrass beds include a variety of polychaetes and several snails, crustaceans, and nemerteans.

Below MLLW, and in shallow subtidal zones, biota can be segregated into two rather distinct habitats: eelgrass beds in shallow areas with sand or mud substrates, and beds of large kelps with abundant red algae understory. This latter habitat supports a diverse fauna including juvenile rockfish, cods, juvenile shrimp, and several other fish and invertebrates.

15

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EXECUTIVE SUMMARY

GENERAL

A substantial amount of the crude oil which spilled from the tanker Exxon Valdez on March 24, 1989 was deposited on beaches in Prince William Sound. Major beach clean-up activities began in May and continued throughout the summer of 1989. Several hundred kilometers of shorelines were treated in the sound in 1989 using various manual hydraulic wash and bioremediation (fertilization) techniques; additional manual and mechanical clean-up and bioremediation treatments were applied during the summer of 1990. Significant concerns have been raised regarding the potential effects of these treatments on intertidal habitats and biota, especially those treatments using hot-water, high-pressure washes.

The overall objectives of the first year of this study were to evaluate intermediate-term (one-year) recovery of important littoral (intertidal and shallow subtidal) habitats from the effects of oiling and shoreline treatment, and to assess the influence of hot-water treatments on the nature and rates of recovery.

STUDY DESIGN AND APPROACH

Quantitative field surveys were conducted in Prince William Sound in July and September of 1990 to document environmental conditions in several types of habitats subjected to a variety of disturbances during 1989. Stratified-random sampling was used to assess epibiota and infauna at 28 intertidal sites representing several habitats and degrees of disturbance. Two to three stations were established at each site to represent intertidal elevations (zones) of biological interest. This sample design allowed for monitoring of long-term trends in recovery at sites of known oiling and treatment history. It is well suited (by the level of replicated sampling at each station) for comparisons at specific points in time between pairs of stations with similar habitats but different oiling and/or treatment histories. Because of the limited number of stations that could be sampled in each habitat/oiling/treatment category, and because these stations were not, strictly speaking, randomly chosen, it is less well suited to statistical inference regarding the generalized impacts of oiling and treatment over all areas with similar histories. Nevertheless, the degree of difference in some measured parameters was sufficient to draw some general conclusions regarding impacts.

Habitats of interest were productive rocky and mixed sand/gravel/cobble ("mixed-soft") beaches common in protected embayments, as well as high-energy boulder/cobble beaches. Previous studies in Prince William Sound had demonstrated that major intertidal assemblage dominants (both plants and animals) had survived 3-4 months in heavily oiled habitats. However, significant reductions (50 to 100 percent losses) occurred in all of these dominant species immediately following hot-water, high-pressure washing. Because of these identified adverse impacts, ecological effects of this type of treatment were a major focus for the present research effort.

Within each habitat type, these general categories of beaches were sampled: unoiled (controls or Category 1); oiled but not treated with hot-water washes (untreated or Category 2), and oiled and with high-pressure hot water (treated or Category 3). Information on initial oiling and on shoreline treatments applied at study sites was obtained from NOAA, state, and Exxon records, and personal communications with onsite personnel. Samples were collected for analyses of tissue hydrocarbon levels and population structure of several mollusc species, as well as for sediment hydrocarbons. Intertidal and subtidal eelgrass beds offshore of 10 locations representing all three site categories described above were sampled for growth, condition, and reproductive potential.

RESULTS

Cluster analyses determined that station treatment classifications based on chemical, epibiotic, and infaunal data matched the independently defined site categories derived from agency and Exxon records, and observations of field personnel. Sediment concentrations of polycyclic aromatic hydrocarbons (PAH) were significantly lower at unoiled control stations than at all oiled stations (untreated and treated), but there was no significant difference in mean PAH between untreated and treated stations. On the average, sediment PAH concentrations at untreated sites were highest at upper elevations while at treated sites, were highest at lower elevations. This suggests that intrusive treatment acted to move some hydrocarbons from the upper beach downslope; this pattern was not, however, statistically significant.

Tissue PAH in two grazing species (littorine snails and the blue mussel) showed positive relationships with site oiling and treatment histories (higher at untreated than at control and higher at treated than at untreated) while two predatory species (a drill and the sun star) did

not. PAH levels in predators were lower than in the primary consumers, indicating that biomagnification was not occurring in components of the food web examined.

Treatments applied in 1989 resulted in a range of effects on intertidal assemblages. Much of the variability apparently resulted from differences in the timing, nature, duration, and intensity of treatment. Effects of hot-water washing in 1989 remained evident at treated sites in 1990. Some treated rocky beaches contained remnants of abundant pre spill populations of barnacles, mussels, and rockweed; others were stripped to bare rock at mid and upper intertidal elevations and showed relatively little colonization by early fall of 1990. These beaches had significantly lower abundances of several community dominants such as rockweed, limpets, and littorine snails than did other oiled rocky beaches that received less severe or no treatment (i.e., untreated), or were not oiled (i.e., control). At sites falling into the latter two categories, community dominants were similar and significant colonization occurred in 1990.

Infauna on unoiled sand and gravel beaches was dominated numerically by polychaetes, bivalves, and crustaceans. Protected sand and gravel beaches were severely affected by high-pressure treatments which greatly altered beach morphology, regardless of water temperature. Finer sands and gravels were flushed from upper intertidal elevations, often burying the lower beach in several centimeters of sediment. This probably contributed to significant reductions in infauna (e.g., total abundance, diversity, and species richness in July, as well as densities of polychaetes and bivalves in both months) at treated beaches. In contrast, oiled but untreated sand and gravel beaches had a richer and more varied infauna, similar in most instances to that at unoiled control sites.

Examination of populations of three mollusc species (blue mussel, Sitka periwinkle, and a drill) suggests that these species may be experiencing some sublethal effects from oiling and/or treatment. Growth and mortality rates of the mussel and the periwinkle appeared to be affected adversely at oiled sites. The drill, an important predatory snail in the study area, apparently damaged by oiling and treatment, was not sufficiently abundant at untreated or treated sites to allow quantitative evaluation of population characteristics. The condition of molluscs, based on length/weight relationships, was generally poorer at treated and untreated sites than at control sites.

Several aspects of eelgrass biology appeared to be affected of oil contamination. Most important were rhizome/root biomass and density of flowering shoots, seeds, and young-

of-year plants. Rhizome/root biomass was higher at oiled sites. Density of each of the reproductive elements was highest at control sites and lowest at the oiled sites. It is significant that several of the more important differences indicated reduced reproductive potential at oiled sites as this could lead to long-term reductions in density and biomass of eelgrass beds, an important primary producer in many areas of the sound.

Additional analyses have not been completed at this time, including those for PAH levels in tissues from September collections. However, in comparisons of treated and untreated sites, the existing body of data suggests that high-pressure, hot-water treatment displaced some deposited oil from upper to lower intertidal and shallow subtidal elevations. This resulted in reduced abundances of dominant epiflora, epifauna, and infauna, including important hardshelled clams, delayed or depressed mollusc recruitment, depressed mollusc growth and survival rates, and possibly caused significant adverse effects on subtidal eelgrass beds. These conclusions are consistent with other study results reported in 1989 before and after hot-water treatments at two experimental sites in Prince William Sound.

CONCLUSIONS

The effects and extent of shoreline treatment in areas affected by the *Exxon Valdez* oil spill will greatly complicate assessment of the long-term impacts of treatment and the oil alone. Because much of the heavily oiled shoreline was washed with high-pressure hot water at least once, and because so little of the oiled shoreline was left untreated, only a limited number of areas remain where comparisons may be made to distinguish between effects of oiling and the effects of oiling plus treatment. Lack of specificity in the available treatment information (e.g., equipment, temperature, duration, bioremediation application rates, and repetitions) also complicates separation of effects of individual treatment approaches.

Nevertheless, the results from this study to date provide a strong basis to argue that conditions spanning a broad spectrum of biological properties reflect both the influences of hydrocarbon contamination and intrusive shoreline treatment. The high number of cases in which the null hypothesis of no impact from oiling and/or treatment was rejected is impressive. It is clear, based on the number of rejections and the high levels of significance observed in many cases, that the data provided by this study strongly support the conclusion that hydrocarbon contamination and high-pressure, hot-water treatment each caused major adverse impacts to the intertidal biota of western Prince William Sound, but that the effects of the treatment predominated. Moreover, it appears likely that the treatment, while



removing oil from the upper and mid-intertidal zone, where its effects were somewhat restricted to relatively tolerant organisms such as barnacles, rockweed, and mussels, transported the remobilized oil into the lower intertidal and shallow subtidal zones, where the oil was placed into contact with relatively more sensitive and productive organisms such as hardshelled clams and crustaceans.

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YEARS AFTER THE
1989 PRINCE WILLIAM
SOUND SPILL**



By Edward H. Owens, Ph.D.
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TABLE OF CONTENTS

GLOSSARY	iv
SUMMARY	1
INTRODUCTION	4
Prince William Sound	4
Kenai-Kodiak Region	5
OBJECTIVES AND METHODS	9
Program Objectives	9
Study Sites	9
Field Program	11
Field Methods	13
Data Reduction	14
Additional Surveys	15
RESULTS	16
Beach Morphology Changes	16
Surface Oil Cover Changes	20
Subsurface Oil Conditions	38
Changes in Sediment TEH Data	42
DISCUSSION	45
CONCLUSIONS	48
Program	48
General Observations	48
Oil Cover	48
Subsurface Oil	49
Sediment TEH Data	49
Beach Changes	49
Winter Winds and Waves	49
Biological Observations	50
REFERENCES	51
APPENDIXES	
A. Site Location Maps	A-1
B. Photographs	B-1
C. Selected Beach Elevation Profiles	C-1
D. Surface Oil Cover Data	D-1
E. Seal Island Wind Data	E-1
F. Winter Breaker Height Data	F-1
G. Summary of Biological Results	G-1

FIGURES

1	Summary of Changes in Surface Oil Cover at Detailed Monitoring Sites	3
2	Regional Location Map	6
3	Prince William Sound Site Location Map	7
4	Kenai-Kodiak Region Site Location Map	8
5	Surface Oil Cover Versus Time	22
6	Transect Surface Oil Cover Changes Over Time	24-25
7	Smith Island Initial Surface Oil Changes Over Time	34
8	Subsurface Pit Sketch/West Herring Bay	39
9	Subsurface Oil Changes Over Time/Sleepy Bay, Site AP-13	40
10	Subsurface Pit Sketch/South Point Helen, Site AP-10	42
A-1	Site Location Map/Smith Island	A-2
A-2	Site Location Map/Knight Island	A-3
A-3	Site Location Map/Green Island	A-4
A-4	Site Location Map/Latouche Island	A-5
A-5	Site Location Map/Evans Island	A-6
A-6	Site Location Map/Elrington Island	A-7
A-7	Site Location Map/Kenai Peninsula	A-8
A-8	Site Location Map/Afognak Island	A-9
A-9	Site Location Map/Katmai National Park	A-10
C-1a	Elevation Profile/AP-1, Transect 8	C-2
C-1b	Elevation Profile/AP-1, Transect 10	C-2
C-2	Elevation Profile/AP-10, Transect 5	C-3
C-3	Elevation Profile/AP-16, Transect 3	C-3
C-4	Elevation Profile/AH-3, Transect 2	C-4
C-5a	Elevation Profile/AK-2, Transect 3	C-4
C-5b	Elevation Profile/AK-2, Transect 7	C-5
C-6	Elevation Profile/AK-3, Transect 8	C-5
C-7	Elevation Profile/AK-5, Transect 6	C-6
C-8	Pre- and Post-Berm Relocation Profiles/AP-13W, Transect 26	C-6
D-1	Surface Oil Cover Map/Northeast Smith Island, Site AP-1	D-4
D-2	Surface Oil Cover Map/Foul Pass-Ingot Island, Site AP-4	D-5
D-3	Surface Oil Cover Map/Northeast Latouche Island-North, Site AP-12	D-6
D-4	Surface Oil Cover Map/North Evans Island, Site AP-15	D-7
D-5	Surface Oil Cover Map/Southwest Elrington Island-East, Site AP-16	D-8
D-6	Surface Oil Cover Map/Southwest Elrington Island-Southwest, Site AP-18	D-9
D-7	Surface Oil Cover Map/North Windy Bay, Site AH-2	D-10
D-8	Surface Oil Cover Map/Perevalnie Point, Site AK-1	D-11
D-9	Surface Oil Cover Map/Ushagat Island, Site AK-5	D-12

E-1	Seal Island Wind Data	E-4-5
F-1	Estimated Breaker Heights for AP-13W, Sleepy Bay	F-4
F-2	Estimated Breaker Heights for AP-1, Northeast Smith Island	F-5
F-3	Estimated Breaker Heights for AP-4, Foul Pass, Ingot Island	F-6
F-4	Estimated Breaker Heights for Chenega Island	F-7
F-5	Estimated Breaker Heights for Bay of Isles	F-8
F-6	Time-Lapse Camera Site Locations in Prince William Sound	F-9
G-1	Barnacle Spat Comparisons	G-7
G-2	Juvenile and Adult Barnacle Comparisons	G-8
G-3	Mussel Comparisons	G-9
G-4	Fucus Recruit Comparisons	G-10
G-5	Juvenile and Adult Fucus Comparisons	G-11
G-6	Limpet Comparisons	G-12
G-7	Littorinid Snail Comparisons	G-13

TABLES

1	Kenai-Kodiak Region Site Locations and Characteristics	10
2	Prince William Sound Site Locations and Characteristics	10
3	Summary of Wave-Energy Environments and Initial Oiling Characteristics of the Study Sites	12
4	Summary of Winter Field Activities/September 1989 to March 1990	12
5	Summary of Data Collected	13
6	Percent of Surface Oil Cover	21
7a	Selected Study Sites/General Characteristics	26
7b	Selected Study Sites/1989 Treatment Histories	27
8	Changes in Oil Cover by Tidal Zone and Oil Category	32
9	Summary of Average Surface Oil-in-Sediment from the Upper Intertidal Zone	43
D-1	Oil Cover Survey Dates	D-2
D-2	Oil Cover Surveys/Equivalent Oiled Area Data	D-3
E-1	Major Storms	E-3
E-2	Secondary Storms	E-3
F-1	Predicted Spring Tides at Cordova	F-2
F-2	Summary of Breaker Height Observations	F-3

PHOTOGRAPHS

On-Site Photographs (B-1 to B-18)	B-2-6
Breaker Height Videotape (F-1 to F-5)	F-11-12

GLOSSARY

ASAP: August (1990) Shoreline Assessment Program.

Berm: A zone above the beachface that is nearly horizontal and is above the limit of normal wave action.

Bioremediation: Treatment of oiled surface and subsurface sediments by applying phosphorus and nitrogen fertilizer to enhance bacterial breakdown of petroleum.

Energy characterization: Shorelines in the Sound and Kenai-Kodiak are exposed to a variable range of wave energy, dependent on coastline configuration and available *fetch*. Three categories defined for this report are **exposed** (high), **moderately exposed** (moderate), and **sheltered** (low) wave-energy environments. High wave-energy shorelines are those open and exposed to long fetch areas. In general, high-energy shorelines in the Kenai-Kodiak region are subject to much more wave action than those in the Sound. Low wave-energy shorelines are those beaches that are sheltered, such as enclosed bays and inlets, with only very limited fetch areas. Kenai-Kodiak and Sound low wave-energy shorelines are of similar wave-energy exposure.

Fetch: The length of open water over which waves are generated by wind.

FASST: Fast Assessment Shoreline Survey Team ground survey carried out in February 1990.

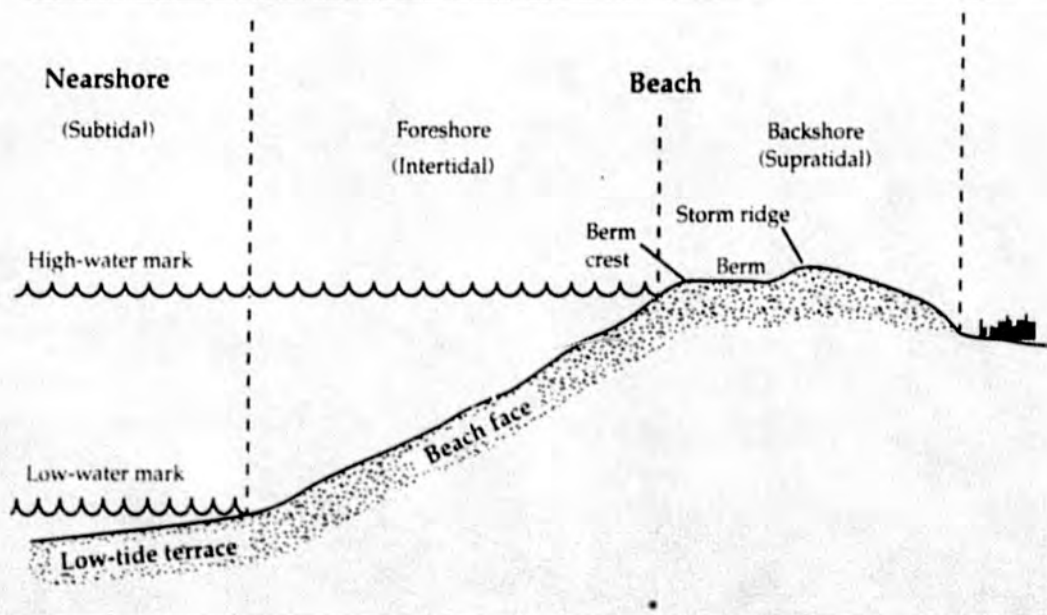
Gravel: Sediments that are a mixture of coarse sand and pebble-size material.

Gravimetric analysis: Determination of the concentration of a component (oil) in a mixture (sediment) obtained by extracting the component from a weighed aliquot of mixture, and then weighing the component.

High-water mark: The higher limit of the tidal water level. **Mean high-water mark** or the mean high-tide mark is the higher limit averaged over time. **Spring high-water mark** or spring high-tide mark is the higher limit of *spring tides*. **Neap high-water mark** is the higher limit of *neap tides*.

Beach Profile With Terminology

This figure shows shoreline terms used in this report.



Katabatic winds: Winds resulting when cold air masses at elevation flow downhill because of their greater density.

Neap tides: Tidal range is reduced when the gravitational pull of the sun is at right angles to, and thus opposing, the pull of the moon. These neap tides occur twice each month, during the first and last quarter of the moon.

Oil band category: Surface oiling was initially categorized by oil band width, where **heavy** oil cover is > 6 m wide; **moderate** oil cover is ≥ 3 m to < 6 m wide; **light** oil cover is < 3 m wide; and splashes are categorized as **very light**.

Oil conditions: Stranded oil was initially described by the following terms: **Length** is distance (m) alongshore, parallel to the waterline. **Width** is distance (m) normal, or perpendicular, to the waterline. **Thickness** is one of the following: **Pooled** is > 1 cm thick deposit; **cover** ranges between > 1 mm (0.1 cm) and < 1 cm; **coat** is < 1 mm, and can be rubbed off; and **stain** is < 1 mm, and cannot be rubbed off. **Range of subsurface oiled interval** is the depth interval of sediment matrix, within which oil is observed, measured from the local sediment surface, not from the tops of adjacent boulders or large cobbles protruding from the sediment.

Oil distribution: Surface oil cover is designated **continuous** where the surface oil covers 90 to 100 percent, **broken** where 50 to 89 percent, **patchy** or **sporadic** where 10 to 49 percent, and **splashes** (splatters or drips) where < 10 percent.

SCAT: Shoreline Cleanup Assessment Team(s) conducted the initial shoreline surveys during the spring and summer of 1989.

Sediment size: Units are defined by the mean diameter of the particles:

Boulder	> 256 mm
Cobble	64-256 mm
Pebble	4-64 mm
Granule	2-4 mm
Coarse sand	0.5-2 mm
Medium sand	0.25-0.5 mm
Fine sand	0.06-0.25 mm
Silt	< 0.06 mm

SSAT: Spring Shoreline Assessment Team survey in April 1990.

Spring tides: Tides that occur when the gravitational pulls of the sun and moon are in the same direction: thus, high tides are higher and low tides are lower than usual. Spring tides occur twice a month, at the new and full moon. The highest spring tides usually occur twice a year at the spring and autumn equinoxes when the sun is overhead at the equator.

Total extractable hydrocarbon (TEH): Concentration of hydrocarbon compounds in a sediment sample, determined for this study using gravimetric analysis.

Transect: A survey line along which regular observations are recorded. In this case, most transects run perpendicular to the shoreline.

SUMMARY

When the "Exxon Valdez" ran aground on March 24, 1989, it spilled approximately 258,000 barrels of oil on the waters of Prince William Sound. Within a few weeks, an extensive monitoring program was begun by Exxon to assess shoreline oiling conditions in the area. This report details that effort.

The long-term shoreline monitoring program was conducted from May 1989 to September 1990 at 28 sites in Prince William Sound and the Kenai-Kodiak region. The program was designed to provide information on changing oiled shoreline conditions that Exxon could use to decide on appropriate treatment activities.

A clear picture emerges of relatively rapid changes over the study period. There is a strong contrast between the heavily oiled study sites established in 1989 and the clean bedrock coasts and beaches that characterized most of the shoreline after the 1989-90 winter months. This contrast is documented by the monitoring program.

The monitoring program focused primarily on time-series observations of surface oil cover. This data set was supplemented by observations from other studies or surveys. All studies show that the 1989 treatment activities accelerated the natural cleaning, particularly of heavily oiled beaches. Study sites that were not extensively oiled also were cleaned rapidly, but largely as a result of natural processes. In sheltered areas, the treatment program flushed out most of the bulk oil in much the same way that waves and tides were able to wash exposed coasts. This bulk oil removal enabled weathering and degradation processes to progress more rapidly than would otherwise have occurred. On exposed coasts, wave abrasion and flushing were the predominant processes, whereas physico-chemical weathering and biodegradation were important following flush-and-flood treatment on sheltered coasts. The combined result of treatment and natural cleaning was that the majority of shorelines retained little or no oil by the end of the summer of 1990. Results of the study to date show the following:

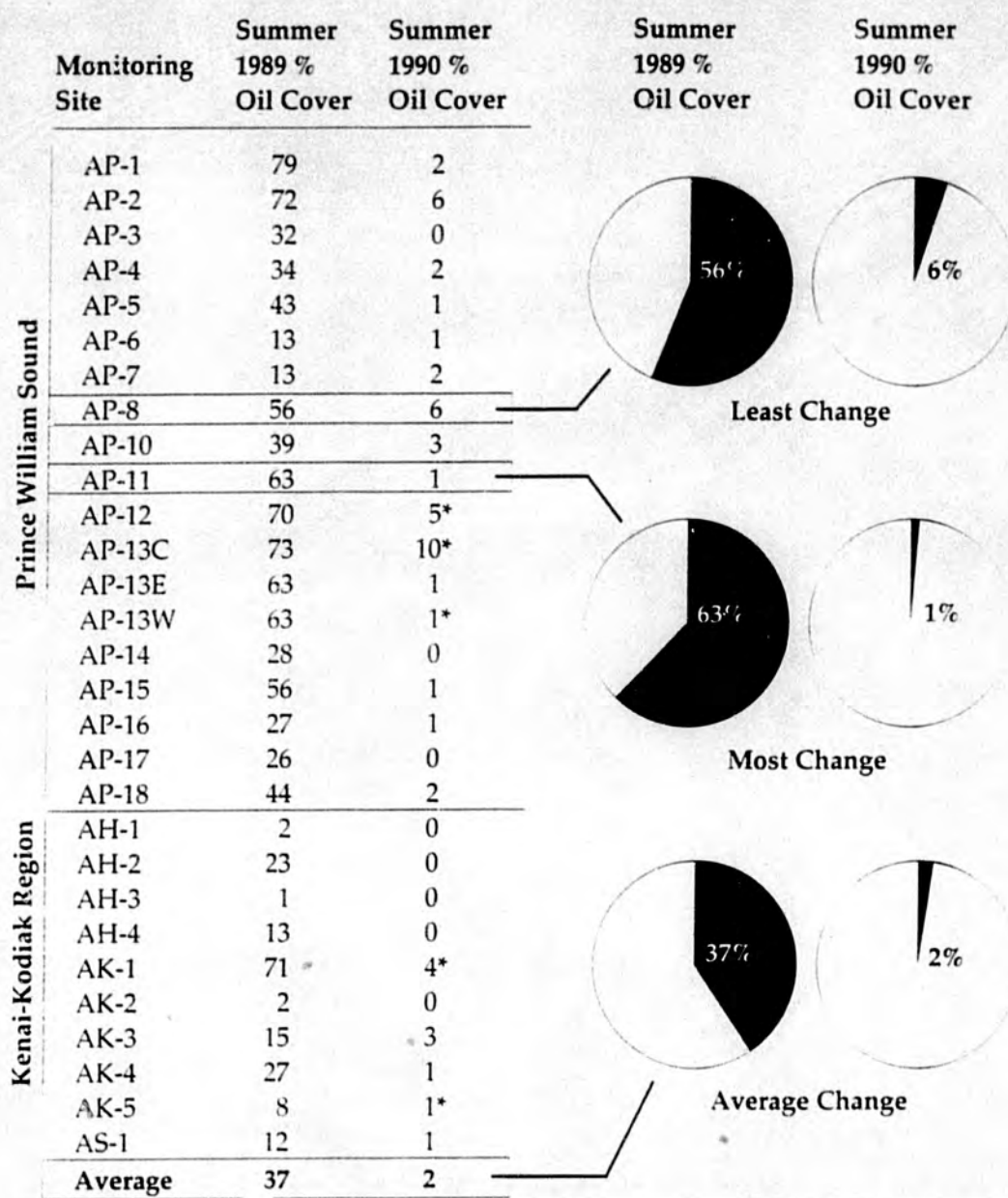
- The majority of the 28 study sites were initially heavily oiled, thus biasing the study toward worse-case conditions.
- By September 1990, 20 of 27 sites (one site was not revisited after August 1989) had an oil cover of 2 percent or less, and eight of these sites had no visible oil (Figure 1, on page 3).
- The combined average surface oil cover area of all the Prince William Sound study sites dropped drastically between May 1989 (six sites), from 46 percent of the total observed area to less than 2 percent by September 1990.
- The changes documented at the study sites resulted from a combination of Exxon's cleanup activities during the summers of 1989 and 1990 and the natural removal of oil by wave action and biophysical weathering. During the 1989 summer treatment

program, washing accelerated rates of natural cleaning by removing bulk oil. This activity enabled physical, chemical and biological degradation processes to proceed at faster rates than would have been possible with higher oil concentrations.

- Field data from the study sites show that oil cover reduction was generally proportional to the level of treatment (flushing) effort. A significant reduction in oil cover and amount of oil on the shoreline occurred during the summer of 1989 before the September survey.
- Rates of oil removal over the 18-month study period varied between sites because of a number of factors, including substrate character, available wave energy at the shoreline, and the treatment history of the site.
- Natural cleanup of the oiled shorelines occurred at rates that were faster than expected, particularly in sheltered, relatively low wave-energy environments. Oil removal at sheltered locations may be attributed to the interaction of fine sediment particles and seawater with the residual surface oil coating, to biodegradation, and to low levels of wave activity.
- Oil residues at the end of summer 1990 were generally limited to rock crevices or were beneath boulder or cobble sediments where neither wave action nor treatment activities had reached after 18 months. Subsurface oil remained at a few locations, where oil was able to penetrate into the large spaces between sediments. Bedrock accounts for an estimated 72 percent of the oiled coasts in Prince William Sound, and where oil did remain on the shores in September 1990, it was only in the form of surface patches. Beaches are predominantly gravel, and penetration on these beaches was limited to the top few centimeters by the presence of fine-grained sediments (sands).
- Oiled sediments that remained on the backshore of beaches in 1990 were mechanically relocated into the upper intertidal zone where available oil was removed and where oil residues could be reworked and cleaned by wave action.
- The effectiveness of the cleanup activities and natural recovery was shown in September 1990 by the small amounts of oil residue and the general lack of asphalt pavements, which typically form on heavily oiled, gravel beaches.
- Oiling conditions were found to be highly variable within a study site, and data analysis indicates that single transects may not always be representative of the overall distribution and character of oil on a beach.

Figure 1
Summary of Changes in Surface Oil Cover at Detailed Monitoring Sites

On average, surface oil for the monitoring sites reduced from 37 percent to 2 percent in about a year.



*Before berm relocation.

- Key organisms were observed to be similar in abundance and distribution on most oiled and non-oiled sites in September 1990.
- Ecological recovery appeared to be enhanced at some sites where 1989 treatment activities (flush and flood) were able to remove the majority of the bulk oil.

Several previous spills have occurred in similar coastal environments, for example, the "Arrow," "Metula," and "Nestucca" spills, and the Baffin Island Oil Spill (BIOS) experiment. Experience gained from these spills was of great assistance in evaluating oiling conditions in Prince William Sound and the Kenai-Kodiak region, but no other spill has been studied to the same degree as has this. As a result, a more accurate picture emerges of how and at what rates stranded oil is removed under varying coastal conditions.

INTRODUCTION

A site-specific, long-term monitoring program of shorelines oiled by the spill was initiated by Exxon in May 1989 and continued at regular intervals through the winter to the most recent survey in September 1990. Twenty-eight locations were staked during the spring and summer of 1989 and systematically document the changes in oil cover through time (Figure 1, on pages 6, 7 and 8). Monitoring sites were chosen from a list of heavily oiled sites in the Sound and Kenai-Kodiak region. Monitoring was conducted at monthly intervals from August 1989 to January 1990, and in March, June, and September 1990. Weather conditions affected the program, but 126 out of a possible 168 winter site visits were completed from September 1989 to March 1990.

This report summarizes the data collected from the site surveys through September 1990. The discussion is considered preliminary at this stage of interpretation. Though data reduction is still in progress, the trends and conclusions represent the conditions at the study sites and the changes that have occurred on these shorelines between April 1989 and September 1990. Additional information has been taken from a number of other related studies conducted by Exxon. These studies include:

- An initial shoreline assessment in the summer of 1989;
- A Fast Assessment Shoreline Survey Team (FASST) ground survey in February 1990 in the Sound;
- A Spring Shoreline Assessment Team (SSAT) multi-agency ground survey in April 1990;
- An August (1990) Shoreline Assessment Program (ASAP) multi-agency ground survey;
- A time-lapse photography program at five locations in the Sound conducted between November 1989 and April 1990; and
- A study of beaches where sediments were relocated from the backbeach to the upper intertidal zone during summer 1990.

Prince William Sound

The "Exxon Valdez" grounded on Bligh Reef on March 24, 1989, releasing approximately 258,000 barrels of North Slope crude oil on the waters of northern Prince William Sound. The Sound is a large inland sea with a complex coastline of irregular bays and passages (Figure 2, on page 6). This complexity results from the recent glaciation of this upland region. Tectonic uplift during the most recent (1964) major earthquake caused the emergence of shorelines throughout most of the Sound, with vertical changes on the order of 1 meter (m) in northwestern sections and of 3 m in the south on Montague Island (Plafker 1965). Many beaches, therefore, are young and may not have reached a dynamic equilibrium with wave conditions. The tidal range varies

from 3 m during neap tides to 6 m during spring tides. Waves are locally generated, as north Pacific swells have little effect beyond the narrow straits that connect the Sound to the ocean. Maximum fetch distances reach 100 kilometers (km) in the central, open area of the Sound, although they are generally less than 50 km. Wind velocities vary seasonally and are highest between October and March. The strongest winds are generally from easterly directions (Brower et al. 1988). The resulting wave climate is characterized by a relatively calm summer, and by winter storm events associated with low-pressure systems that pass through the region. Time-lapse photography over the 1989-1990 winter recorded breaker heights greater than 2 m on exposed coasts during storms, whereas in sheltered environments wave heights rarely exceeded 0.25 m.

Less than 20 percent of the shoreline of the Sound was oiled and the physical character of the coastal zone that was oiled is dominated by bedrock outcrops and poorly sorted sediment beaches. Bedrock outcrops form about 60 percent of the oiled shoreline in the Sound. Boulder-covered bedrock platforms represent nearly 12 percent and mixed cobble, pebble and sand beaches form about 28 percent. On exposed shorelines, the mixed sediment beaches commonly have a surface veneer, or armor, of coarse sediments (boulders and cobble) underlain by mixed gravel, sand, cobble, and boulders. Well-sorted cobble and boulder beaches occur on a few open-coast shorelines, but these are not common in the Sound. Fine-grained, well-sorted sediments (sand beaches, mud flats, or marsh depositional environments) are not common in the Sound of Prince William Sound. Stranded logs, however, are a common feature of the upper beach area on most shorelines.

Kenai-Kodiak Region

Oil was carried out of the Sound through the straits that connect the Sound to the Gulf of Alaska (Figure 2, on the next page). The anticlockwise coastal currents then moved the oil west and southwest along the coast of the Kenai Peninsula toward the Kodiak Island-Shelikof Strait region. The shorelines of the Kenai-Kodiak region are similar in many respects to those of Prince William Sound, except that wave-energy levels are considerably greater in Kenai-Kodiak. Open-ocean wave heights are greater than 4 m for approximately 15 percent of the time from October to April (Brower et al. 1988), and the contrast between high wave-energy, open-ocean shorelines and adjacent sheltered, low wave-energy environments is very marked. Fine-grained sediments are supplied to the area by rivers and by erosion, and sandy beaches occur at a few locations. The outer coast beaches are often formed of well-sorted sediments with high storm ridges.

Ice is not an important element of the coastal environment of the Sound or Kenai-Kodiak region, but where the tidewater glaciers reach the sea, ice is the shoreline. Sea ice forms locally at the heads of bays where the surface water is fresh or brackish and can freeze during mid-winter cold periods.

Figures 2, 3, and 4, on pages 6, 7, and 8, show general study areas in Prince William Sound and the Kenai-Kodiak region, plus specific site locations. Detailed maps are placed in Appendix A.

Figure 2
Regional Location Map

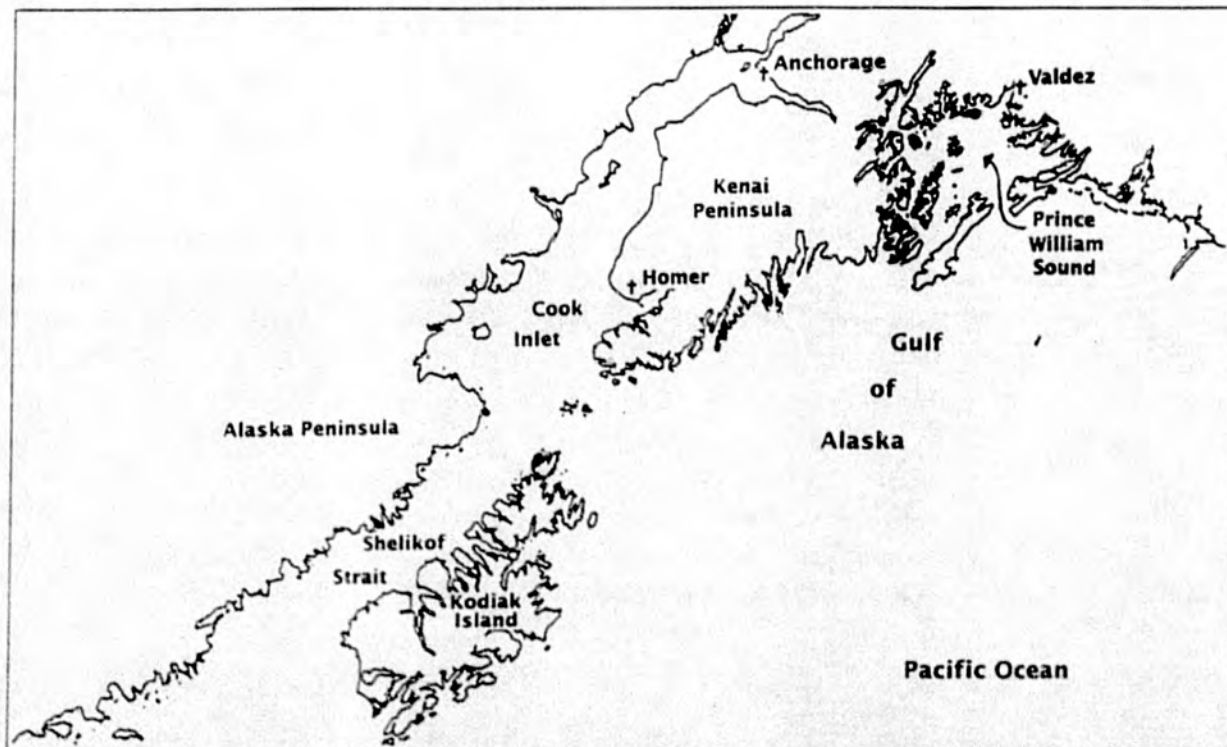
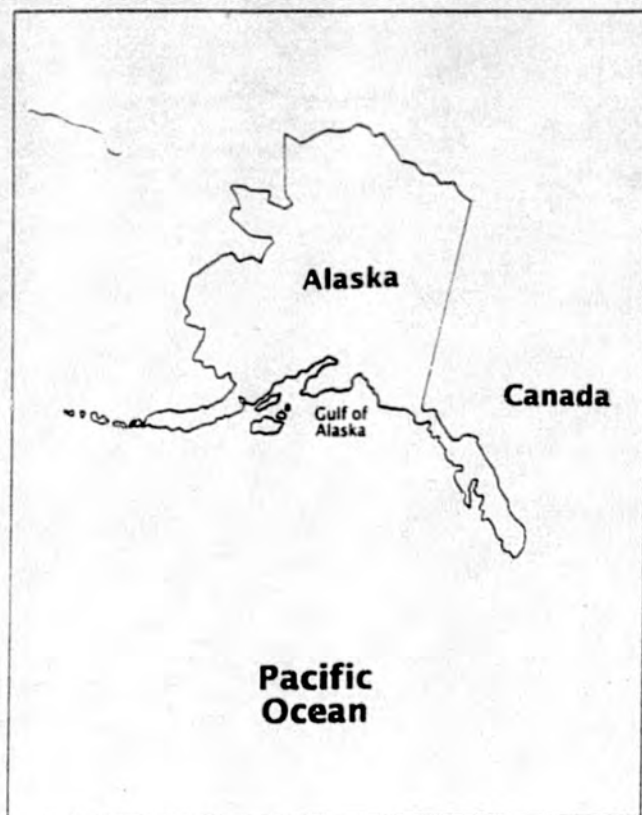


Figure 3
Prince William Sound Site Location Map

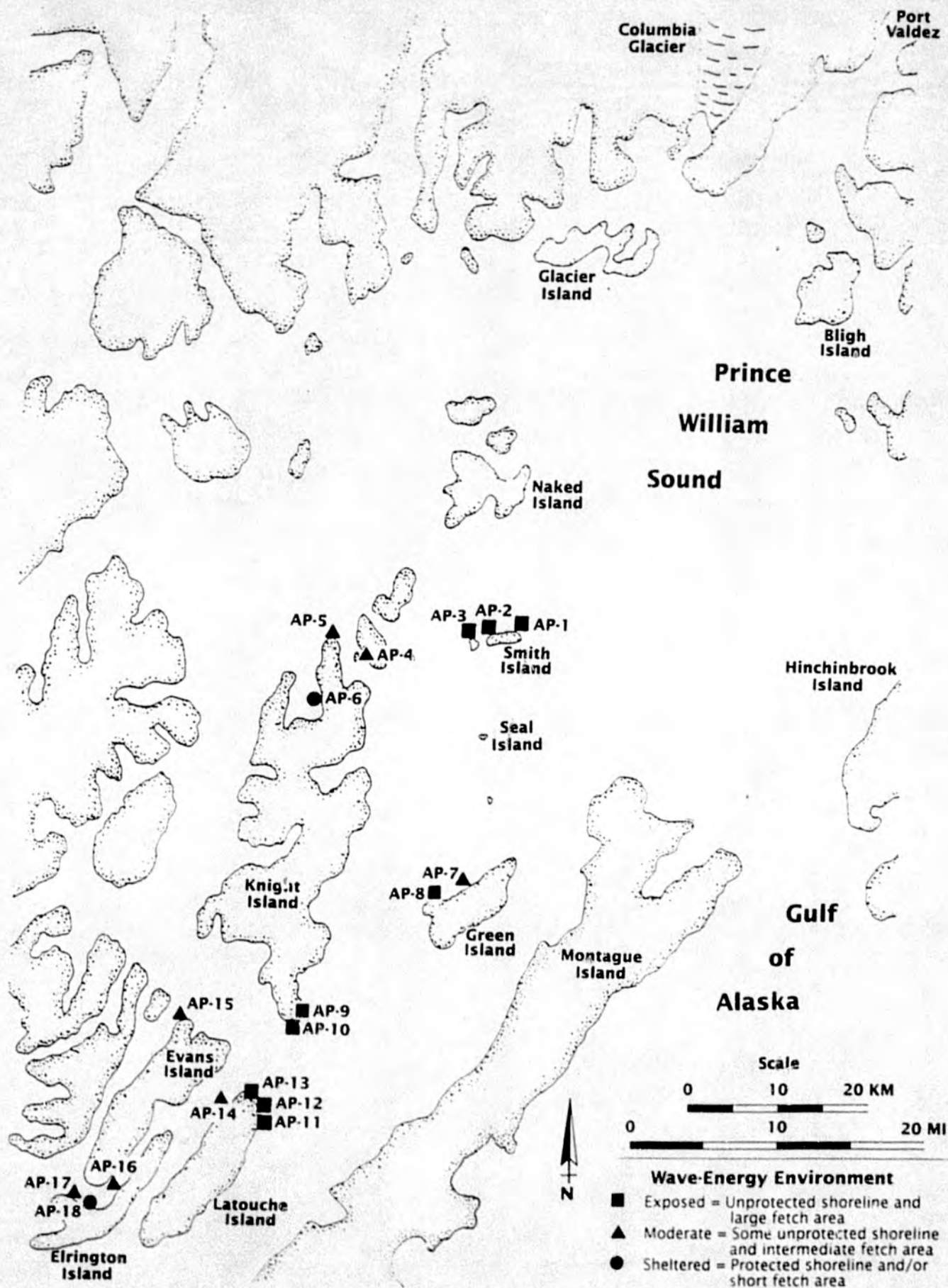
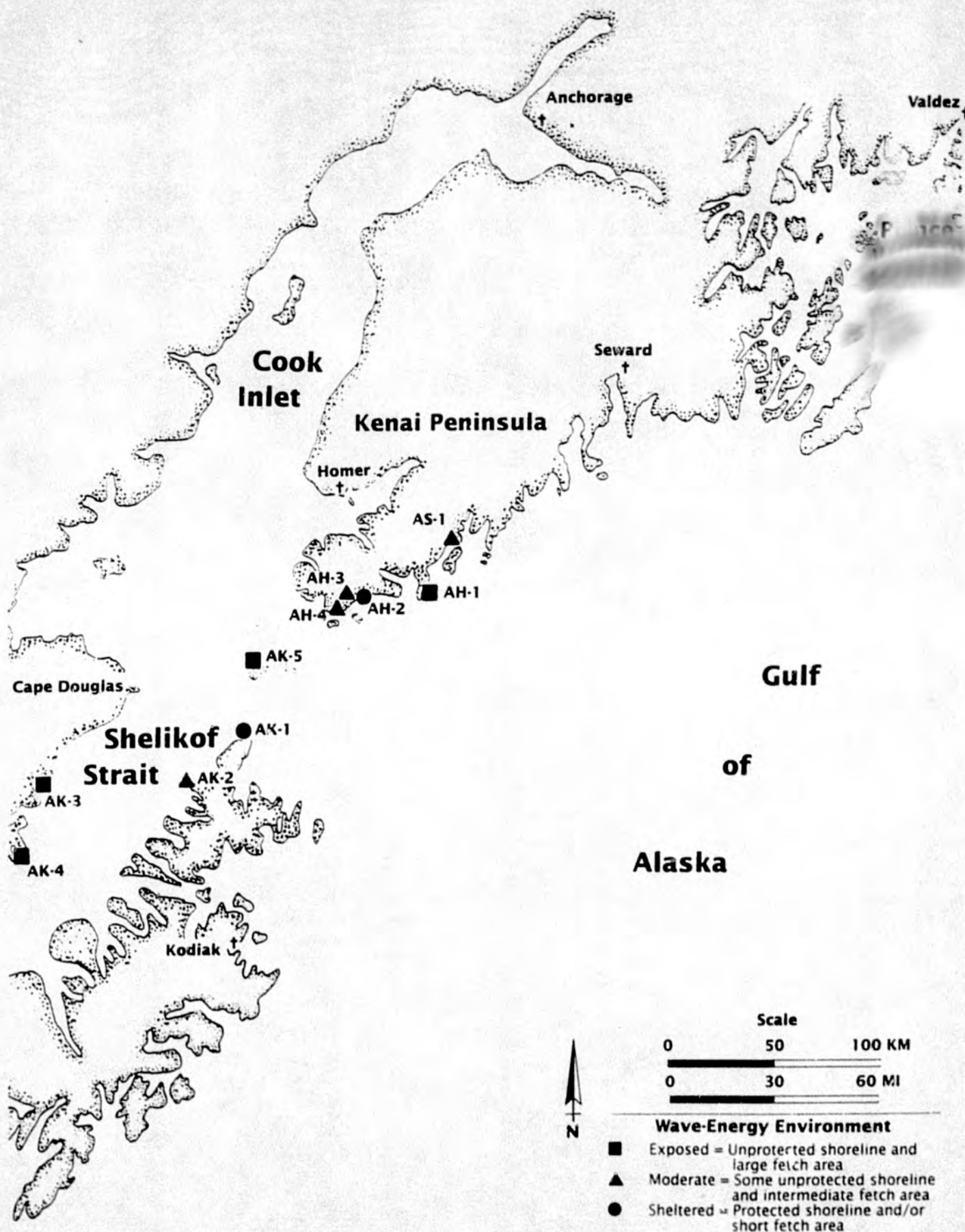


Figure 4
Kenai-Kodiak Region Site Location Map



OBJECTIVES AND METHODS

Program Objectives

The primary objectives of this study were to document and assess the fate and persistence of oil stranded on the coasts of Prince William Sound and the Kenai-Kodiak region after the spill. The program was designed to monitor the distribution of stranded oil on different shoreline types through time. The information was collected to help understand and assess the changing character of oil on the shorelines; it provided input for decisions and planning of appropriate shoreline treatment (Teal 1990). Study sites were chosen to represent the most heavily oiled conditions in the Sound and Kenai-Kodiak region. The field work for the program involved 28 study sites in 1989 and 26 sites in 1990. Surface oil cover and beach elevation measurements were made; sediment samples were collected for total extractable hydrocarbon (TEH) analysis; and test pits were dug to measure oil penetration. These studies were supplemented with detailed photographic and videotape transects of the study sites. This report includes data collected through September 1990.

The program focused on the collection of surface oil cover data, as this was considered to be a key indicator of changing oil conditions through time. Experience from previous studies had identified the difficulties associated with monitoring subsurface oil conditions and oil-in-sediment concentrations on coarse-sediment beaches. However, the study did include limited subsurface and oil concentration data collection on single transects at each site. The subsurface observations in the test pits of the systematic monitoring program, coupled with the TEH analysis, provided information on the character and changes in subsurface oil conditions. The study site observations are supplemented by data from other programs. During 1989, there were no systematic studies of subsurface oiling conditions during the regional surveys, but observations were made during the SSAT (spring 1990) program which enhance the monitoring program data. Although this report focuses on the information obtained as a result of the monitoring program, other observations and data are referenced and used to clarify a number of trends and significant points.

Study Sites

Twenty-eight primary sites were established: 18 in Prince William Sound and 10 in the Kenai-Kodiak region (Figures 3 and 4). Site locations are shown in Figures A-1 through A-9, on pages A-2 through A-10.

The Kenai-Kodiak region sites represent the most heavily oiled beaches in that region, but these were less oiled than the Sound sites at the beginning of the study. The Kenai-Kodiak sites that had the most oil cover were at Ushagat Island (site AK-5), Perevalnie Point (AK-1), Cape Kubugakli (AK-4), and Yalik Glacier Beach (AS-1) (Table 1, on the next page). The majority of the 18 sites in Prince William Sound also had initially continuous, wide-band oil coverage (Table 2, on the next page), and typified the range of substrate and beach dynamics observed in that region.

Tables 1 and 2, on the next page, show the characteristics of 28 study sites. Most sites in the Kenai-Kodiak region were less oiled than the Sound sites (Table 1). During the initial studies, most of the 18 sites in the Sound had continuous oil coverage wider than 6 m (Table 2).

Table 1
Kenai-Kodiak Region Site Locations and Characteristics

Site	Location	Original Oil Band Width	Wave-Energy Environment
AH-1	Gore Point	Medium	Exposed
AH-2	North Windy Bay	Medium	Sheltered
AH-3	Badger Cove	Medium	Moderate
AH-4	Chugach Bay	Medium	Moderate
AK-1	Perevalnie Point	Wide	Sheltered
AK-2	Black Cape	Medium	Moderate
AK-3	Cape Nukshak	Medium	Exposed
AK-4	Cape Kubugakli	Wide	Exposed
AK-5	Ushagat Island	Wide	Exposed
AS-1	Yalik Glacier Beach	Wide	Moderate

Note: Wide band equals > 6 m. Medium band equals 3 to 6 m.

Table 2
Prince William Sound Site Locations and Characteristics

Site	Location	Original Oil Band Width	Wave-Energy Environment
AP-1	Northeast Smith Island	Wide	Exposed
AP-2	Northwest Smith Island	Wide	Exposed
AP-3*	Northeast Little Smith Island	Wide	Exposed
AP-4*	Foul Pass, Ingot Island	Wide	Moderate
AP-5	Passage Point, Knight Island	Wide	Moderate
AP-6	East Herring Bay	Medium	Sheltered
AP-7	Central Green Island	Wide	Moderate
AP-8	West Green Island	Wide	Exposed
AP-9*	North Point Helen	Wide	Exposed
AP-10	South Point Helen	Wide	Exposed
AP-11	Northeast Latouche Island-South	Wide	Exposed
AP-12	Northeast Latouche Island-North	Wide	Exposed
AP-13	Sleepy Bay, Latouche Island	Wide	Exposed
AP-14	Northwest Latouche Island	Wide	Moderate
AP-15	North Evans Island	Wide	Moderate
AP-16	Southwest Elrington Island-East	Medium	Moderate
AP-17	Southwest Elrington Island-North	Medium	Moderate
AP-18	Southwest Elrington Island-Southwest	Medium	Sheltered

Note: Wide band equals > 6 m. Medium band equals 3 to 6 m.

* Not surveyed in 1990.

* AP-4 was originally classified as a sheltered, low-energy site. Based on field observations, particularly during the winter of 1989-90, the site was reclassified as a sheltered/moderately exposed location. Throughout this document, AP-4 appears as either sheltered or moderately exposed because it falls somewhere between these two categories.

A summary of the original oiling conditions and the wave-energy environments for the study sites (Table 3, on the next page) clearly shows that in Prince William Sound the program was biased toward sites with initially heavy oiling conditions.

Field Program

The first set of six sites in the Sound was staked and surveyed in May 1989. The program was expanded to 16 locations in late June to early July 1989 and then to 18 in August 1989. From September 1989 to September 1990, attempts were made on eight occasions to resurvey each location, with the following exceptions:

- AP-3 was not visited after November 1989 because no surface or subsurface oil remained.
- The stakes at AP-9 were removed accidentally by a cleanup crew in September 1989 and were not replaced because surveys of the site were duplicated by those of AP-10.
- Access difficulties by boat, due to winter nearshore wave conditions, and by helicopter prevented surveys of AP-15 from September 1989 to January 1990.

Nine locations in the Kenai-Kodiak region were established and surveyed in late July and early August 1989; a 10th site was added for the October 1989 survey. Attempts were made on eight occasions to resurvey each site from September 1989 to September 1990.

Field data collection was confined to periods when tidal water levels were less than +1.0 m above chart datum during daylight hours. This was a limiting factor between November 1989 and January 1990 when only one in three low tides coincided with daylight periods. A further necessary limitation was the adherence to safe operating practices and standards with respect to wind and wave conditions, resulting in the loss of one in four available working days. By contrast, transportation problems (vessel or aircraft mechanical failures) cost only 4.5 days out of the total 302 field days (Table 4, on the next page). The success of the operational phase of the winter program from September 1989 through March 1990 can be measured by the fact that no accidents or injuries were sustained during this winter program that involved a total of 650 manpower days in a remote, stormy environment. During the whole program, a total of 222 site surveys out of a possible 259 were completed between May 1989 and September 1990.

Table 3, on the next page, shows that no study sites were located in areas of narrow-band oiling (less than 3 m). Table 4 delineates field survey days. Of 302 days during the winter of 1989-90, weather accounted for 69.5 down days and mechanical problems for 4.5.

The field data set from the study sites upon which this report is based is summarized in Table 5, on page 13.

Table 3

Summary of Wave-Energy Environments and Initial Oiling Characteristics of the Study Sites

Prince William Sound		Oil Band Width		
Wave-Energy Environment		Narrow <3m	Medium 3-6m	Wide >6m
	Exposed	0	0	9
	Moderate	0	2	5
	Sheltered	0	2	0
Kenai-Kodiak Region		Narrow <3m	Medium 3-6m	Wide >6m
Wave-Energy Environment	Exposed	0	2	2
	Moderate	0	3	1
	Sheltered	0	1	1
Total Number of Sites		0	10	18

Table 4

Summary of Winter Field Activities/September 1989 to March 1990

	Total Field Survey Days	Weather Down Days	Mechanical Down Days	Total Days
Prince William Sound	107	22.5	1.0	130.5
Kenai-Kodiak Region	121	47.0	3.5	171.5
Total	228	69.5	4.5	302.0

Field Methods

Beach elevation and surface oil cover data were collected by coastal geologists on transects running approximately perpendicular to the shoreline. Each transect (profile) was controlled by backshore stakes that provided the line and starting point for the profile. Transects were generally spaced 20 m apart, although this distance was not used at all locations.

Table 5
Summary of Data Collected

From May 1989 to September 1990, 222 site visits were made. This report details data collected during those surveys.

1989	May	June/July	Aug.	Sept.	Oct.	Nov.	Dec.
Sites Visited	6	22	21	27	24	14	18
Elevation Profiles	81	173	91	122	66	29	45
Oil Cover Transects	83	242	200	232	207	111	174
Samples Collected	N/A	N/A	N/A	126	130	123	143
Subsurface Pits	4	27	25	94	65	86	108
Biological Transects	N/A	N/A	N/A	42	29	12	17
1990	Jan.	March	June	Sept.	Total for 1989 & 1990		
Sites Visited	20	23	28	19	222		
Elevation Profiles	35	35	269	93	1,039		
Oil Cover Transects	163	165	269	226	2,072		
Samples Collected	113	108	175	144	1,062		
Subsurface Pits	85	65	64	84	707		
Biological Transects	20	18	28	17	183		

N/A: Not applicable

Beach elevation change was generally determined at 2-meter intervals along the transect line. Surveys were performed using the Emery method, which employs two calibrated stakes and either the horizon or a bubble level to determine the horizontal plane (Emery 1961). The precision of this method, as used in this program, is ± 0.5 centimeter (cm)/reading if the rods are read to the nearest centimeter. The precision of elevations was checked by closing the surveyed transects; that is, elevations were surveyed back up the beach to the original starting point, and the difference from zero was calculated. For each survey, the average closing errors were equal to, or less than, the target of 0.5 cm/reading. The majority of closing errors were less than 10 cm for the entire transect. This error is acceptable because placing the stakes among boulders and cobbles along the beach may easily alter relative elevations by more than this amount.

Visual estimates of surface oil cover were made along the same cross-beach transects. Each oil cover observation represents the average value for the area 2.5 m on either side of the transect line and 2 m landward of the measurement point. This standard observation covers an area of 10 square meters (m^2) per reading.

Several test pits were dug in the beaches during each survey to determine the depth of oil penetration into the sediments (Photograph B-4, on page B-2). Pits were offset slightly from the transect lines to avoid artificially changing the oil cover observations. Many of the study beaches are dominated by boulders and cobbles, which made it impractical to dig pits or to estimate the downward extent of oiling.

Bulk surface and subsurface sediment samples were collected for gravimetric analysis of total extractable hydrocarbons (TEH). These grab samples usually were collected along two of the transects per site, at approximately equal intervals down the beach. Samples were placed in prelabeled 1-gallon (4-liter) bags and stored at ambient temperature until analyzed. This technique was designed to assess trends of oiling conditions and not to measure total amounts of oil present on a beach.

Photographs were taken to document field methods and the general appearance of the study sites. These photographs consisted mainly of overview shots of the area, surface sediments, oiling, and the test pits. A videotape record was made, generally on one of the transect lines, across the beach during each survey.

Biological transects were surveyed at the time of each site visit by coastal ecologists to document the distribution and abundance of major intertidal macro-species. These cross-shore transect surveys also involved photo documentation and data collection to monitor relative rates of recruitment. This data set is not included in this report, but a brief summary of the results, prepared by Dr. K. Critchlow, is given in Appendix G.

Data Reduction

The results of the elevation and oil cover surveys were transferred from field data sheets to spreadsheets from which a variety of calculated and summary values were generated. The data were then imported into graphics software to plot oil cover and elevation data versus distance along a transect for each survey date. This graphics package facilitated overlaying data from different field surveys.

In the data tables presented in this report, the term "total observed area" refers to the total area (in square meters) of beach observed during a survey. This value multiplied by the visual estimate of surface oil cover, expressed as a percent, provides the "equivalent oiled area" (in square meters). For example, a surface oil cover value of 80 percent over a total observed area of 10 m² at a point on a transect line gives an "equivalent oiled area" of 8 m². This follows the method developed by Owens et al. (1987).

The lengths of the transects that could be surveyed varied from one survey to the next because of tidal stage during the survey, weather conditions, and time available to conduct the survey. This variability makes direct comparison of unmodified data between surveys difficult.

The variability between the areas surveyed on the site visits may be handled by using a percentage oiled area, which is a term that expresses the sum of all equivalent oiled area values relative to the total surveyed area and is an aggregate of all oil cover observations.

Additional Surveys

The data from the monitoring program provide site-specific information through time. To evaluate the results in the context of the region as a whole, some data collected as part of systematic ground surveys have been included. These surveys were initiated and coordinated by Exxon and conducted by Woodward-Clyde coastal geologists and ecologists following a standardized methodology to ensure compatibility between survey teams and between surveys conducted at different times (Owens and Teal 1990a). Regional ground surveys were carried out in the summer of 1989 (Shoreline Cleanup Assessment Team - SCAT), February 1990 (FASST), April 1990 (SSAT), and August 1990 (ASAP).

One aspect of the 1990 shoreline treatment program involved the movement of oiled sediments from backbeach areas, where they remained unaffected by wave action, into the upper intertidal zone, where they could be treated by cleanup crews and abraded and cleaned by waves. Beach surveys were conducted at all sites where berm relocation was carried out before and after the sediment was moved. These surveys involved the measurement of elevations along cross-beach transects in the same manner as the surveys carried out at the long-term monitoring sites. Sediment relocation was used as a treatment technique at six of the long-term study sites.

As part of the winter monitoring program, time-lapse cameras were set up at five locations in Prince William Sound, including three of the long-term study sites (AP-1, AP-4, and AP-13). The photographs provide a time-series record of intertidal beach sediment and morphology changes and of breaker heights from November 1989 to April 1990.

RESULTS

Documented changes of shoreline conditions in Prince William Sound and the Kenai-Kodiak region are discussed from an analysis of the following data sets:

- Beach morphology;
- Surface oil cover;
- Subsurface oil observations; and
- Oil-in-sediment concentrations.

Surface oil cover is the most useful and accurate index of changing oil conditions (Humphrey et al. 1990). These data show that the quantity of oil on the shoreline has been reduced considerably, initially as a result of Exxon's cleanup operations, and later by natural cleaning through wave action and biophysical degradation. Experience from other oil spills in similar coastal environments suggests that almost all of the remaining oil will be fully degraded within the next few years.

A considerable database had been developed as a result of the monitoring program (Table 5) and it is beyond the scope of this report to comprehensively review all aspects of the information generated to date. The discussion contained in this report therefore focuses on key trends and observations. These trends are substantiated by other field observations and by the regional survey results.

Beach Morphology Changes

Changes in the surface configuration of beaches were monitored at the 28 study sites by repeated surveys of elevation along transect lines. The data provide a record of the net erosion and deposition of beach sediments in response to wave action. Additionally, beach morphology changes were recorded by time-lapse photography during the winter at two of the exposed, high wave-energy sites (AP-1 and AP-13) and one relatively sheltered site (AP-4) in the Sound.

Little change occurred during the relatively calm summer months because winds were generally light and, therefore, did not generate high-energy waves. Intense, low-pressure systems passing across the region during winter generated storm waves capable of redistributing and transporting even coarse-grained beach sediments such as boulders. In general, the largest beach changes occurred during winter on exposed sections of the coast, where the full force of breaking waves was spent on the shoreline. The winter erosion stage was followed by spring buildup as the eroded material was returned to the beach zone by constructive wave action.

During this program, more than 1,000 elevation transects were surveyed at the study sites. Representative examples from eight of the sites are given in Appendix C and discussed on the following pages in

order to highlight some of the observed changes. Beach profiles provide a record of long-term or net elevation changes that resulted from wave action between the survey dates. Time-lapse photography at the exposed AP-1 and AP-13 sites documents the almost continuous redistribution of sediments and the cycles of change that characterize these high wave-energy sites.

Prince William Sound Study Sites

Of the study sites that were regularly visited within the Sound, the greatest observed change occurred on northeast Smith Island (AP-1) (Photographs B-5 through B-10, on pages B-3 and B-4). This site is located on a straight section of shoreline with open exposure to waves from all northerly directions (Figure A-1, on page A-2). The beach is a mixture of granules, pebbles, cobbles, and boulders that rest as a relatively thin (1 m) veneer on a bedrock platform. Between the summer and mid-September of 1989, the western section of this exposed beach showed significant erosion in the vicinity of Transects 1 and 2 (Figure D-1, on page D-4). The eroded sediments had not been returned by June 1990 and were apparently transported to the east and deposited in the vicinity of Transects 9 and 10. This alongshore transport suggests strong wave action from a northwest direction. At the same time, the sediments in the central section of the beach (near Transect 8) were eroded and reworked down to the underlying bedrock platform (Figures C-1a and b, on page C-2). The profile data from this site show that:

- The western section was cut back 4 m laterally and eroded 1 m vertically (Photographs B-9 and B-10, on page B-4).
- The central section was eroded 0.5 m vertically during the winter, with the lowest elevations measured by the March 1990 survey; by June 1990, it was rebuilt to the same elevation as during June 1989 (Figure C-1a, on page C-2).
- The eastern intertidal zone was built up as much as 0.5 m (Figure C-1b, on page C-2).

The redistribution of these sediments had a profound effect on residual oil. Abrasion of oil-coated or oil-stained materials occurred as the sediments were moved around by breaking waves. At this site, the sediments were subject to high wave-energy conditions and to continuous reworking and redistribution, so most material within the zone of wave action was clean by the time of a site visit in November 1989. The abraded oil was washed from the beach by wave action and dispersed to be broken down by physical, chemical and biological processes.

Beach elevation changes recorded at the northeast Latouche Island site (AP-12) provide further examples of intertidal sediment reworking. This predominantly pebble-cobble beach is located in a broadly concave section

of coastline exposed to waves from north to southeast directions. Beach sediments at this site were reworked to depths on the order of 0.5 to 0.7 m by winter erosion, followed by spring-summer recovery.

Changes recorded at less exposed sites were less dramatic, but erosion of 0.2 to 0.3 m in the middle and upper intertidal zones was observed at most sites because of winter wave action (e.g., AP-16, Transect 3; Figure C-3, on page C-3). Oil was removed at sheltered sites because even small waves were able to abrade and erode the oil, which was on the beach surface because fine-gravel sediments inhibited penetration.

With storms passing through the region, beach erosion was accompanied by deposition of the intertidal sediments in the adjacent nearshore subtidal zone. Storm events were interspersed with periods of beach recovery when sediments were returned to the beach from the subtidal zone as bars or ridges that migrated up the beach under constructive wave action. This sequence of storm-wave erosion and ridge recovery was observed on several occasions in the time-lapse photography from the Sleepy Bay study site (AP-13) (Photographs F-1 to F-5, on pages F-11 to F-12).

Not all exposed sites underwent major changes. The high-energy, cobble-boulder beach at South Point Helen (AP-10) showed virtually no elevation changes in the middle and lower intertidal zone through the winter (Figure C-2, on page C-3). This lack of change was a result of the well-packed, coarse surface sediment layer that protected the underlying beach sediments against wave energy in that section of the beach. The sediments that formed the armor layer were moved by wave action, so surface oil was abraded. The armor, however, prevented subsurface sediment reworking and thus limited the amount of oil that could be removed by winter storms.

Beach transect data from study sites where sediment relocation was carried out provide valuable information on the effects of that program. For example, at AP-13, in August 1990, a 0.5 meter-high swash ridge migrated up the beach within three days after relocation of sediments from the berm area to the intertidal zone, as waves worked to restore an equilibrium profile (Figure C-8, on page C-6).

Kenai-Kodiak Region Study Sites

Beaches at the exposed Kenai-Kodiak region study sites (Gore Point, AH-1; Black Cape, AK-2; Cape Kubugakli, AK-4; and Ushagat Island, AK-5) underwent major erosion over the winter months, with surveyed beach elevation changes in excess of 1 m at all of these locations. Clearly, any oil that had been deposited within those zones of beach erosion was reworked, washed, abraded, dispersed and degraded. Profiles from AK-2 (Figure C-5b, on page C-5) show:

- A progressive lowering of the beach surface by about 1 m between September 1989 and December 1989 with removal of the high-water berm and flattening of the beach profile
- The return of some of the sediment to the beach between December 1989 and June 1990. This beach appears to undergo cycles of erosion and recovery on an annual basis. Oil had been buried by a 2-5 cm layer of clean sediments at the time of the first site visit in July 1989, and the clean layer and buried oil were removed by subsequent wave action by October 1989.

Transect data from the Ushagat Island (AK-5) site, in the Barren Islands group, reflect some of the highest shoreline wave-energy conditions in the region. This wide and low angle, pebble-cobble beach is exposed to ocean swells and storm waves from southwest to northwest directions (Figure A-7, on page A-8). Storms prior to the December 1989 survey transported sediments up the beach, above the normal intertidal zone, to form new storm berms up to 2 m thick (Figure C-7, on page C-6). By March 1990, much of this berm zone on the northern sections of the beach, including all of the areas where oil had been deposited, had eroded to levels below those of the first survey. In contrast, on the southern section of the study site, oil on the berm remained buried by as much as 1 m of clean sediment. In September 1990, this clean overburden was moved aside, and the layer of buried oiled sediments was relocated across the beach to the high-water level, to be reworked by winter wave action.

The Cape Nukshak (AK-3) site is located in Hallo Bay and consists of a boulder beach mixed with sand, gravel, and cobble material. The partially sheltered location is exposed to moderate wave-energy from Shelikof Strait (Figure A-9, on page A-10). The beach transects surveyed at this site showed relatively little change through the summer and fall of 1989. Higher-energy winter waves in this location eroded the middle and lower intertidal zone by as much as 1 m between mid-October 1989 and the beginning of January 1990 (Figure C-6, on page C-5). Wave conditions were not sufficiently energetic to alter the higher sections of the beach, i.e., the storm berm located above the + 5 m level. By June 1990, the beach had rebuilt to the same elevation recorded in the September 1989 survey. A similar pattern of little change before October 1989, followed by a period of erosion, is shown in the second example from a moderate wave-energy environment (Badger Cove, AH-3). This site is located in a cove on the Kenai Peninsula and consists of a cobble and gravel beach exposed to Gulf of Alaska waves from south to southeast directions (Figure A-7, on page A-8). Initially, the oil was buried by a thin layer of clean sediment but this oil was later removed when the beach was lowered about 0.4 m across the middle and lower intertidal zones and up to 1 m in the upper intertidal zone between July 1989 and early December 1989 (Figure C-4, on page C-4). However, at this site the beach had not rebuilt up to the levels of the previous summer by the June 1990 survey.

In contrast to the exposed and moderately exposed wave-energy sites, the North Windy Bay (AH-2) and Perevalnie Point (AK-1) data indicate that these sheltered beaches underwent little change in either beach configuration or sediment distribution during winter. Oil residues were removed at these sites, indicating that physical processes, such as wave action, do operate, albeit at a reduced level.

Surface Oil Cover Changes

Site surveys from May 1989 to September 1990 resulted in 156 site maps for the Sound and 77 for the Kenai-Kodiak region. Surface oil cover data for each survey are summarized as the total (percent) oil cover for each site (Table 6, on the next page). The oil cover value is obtained by dividing the equivalent oiled area by the total observed area, as described on page 14. The trend of decreasing surface oil cover through time is evident from the data (Figure 5, on page 22). Berm relocation and tilling activities exposed subsurface oil and spread oiled sediments from the backshore over the upper intertidal zone at sites AP-1, AP-2, AP-10, AP-12, AP-13C/W, AK-1, and AK-5, and caused an increase in the surface oil cover at AP-12, AP-13C, AP-13W, AK-1 and AK-5 at the time of the September 1990 survey. The objective of relocation was to move oil that was out of reach of 1989-90 winter wave action, and therefore was expected to have a long residence time, into the zone of wave abrasion and cleaning.

The highest average oil cover value (79 percent) was recorded in the Sound at site AP-1 in late June 1989, but by January 1990 the highest site value had decreased to 22 percent (at AP-2). The first zero oil cover value in the Sound was recorded at the exposed high-energy site on Little Smith Island (AP-3) in October 1989, and seven of the 18 Prince William Sound sites had surface cover values of less than 5 percent at the time of the January 1990 survey. By September 1990, 20 of 27 sites had a cover of 2 percent or less, and eight had no visible oil.

The average oil cover value of the six sites in the Sound that were surveyed in May 1989 was 46 percent. The average cover for all of the sites surveyed in January 1990 was 12 percent and had decreased to 2.5 percent in June 1990. One site, AP-2, falls outside of the general trends, with changes occurring at a slower rate than comparable sites. This beach is on the same exposed, high-energy coast as sites AP-1 and AP-3, both of which dropped to low values by mid-winter. The reasons for this variability between nearby sites are discussed on page 38.

The monitoring sites have produced a data set for the Sound that primarily describes changes for heavily oiled shorelines because 14 of the 18 sites originally had an oil band greater than 6 m wide (Table 3). The data may not be directly extrapolated to all of the Prince William Sound coastline because this category accounted for only approximately

Surface oil cover data for surveys from May 1989 to September 1990 are summarized in Table 6, on the next page. The percent of surface oil cover, relative to observation area, at study sites shows a marked decrease through time, as shown by Figure 5, on page 22. Each line is the average of all sites within the three wave-energy categories.

Table 6
Percent of Surface Oil Cover

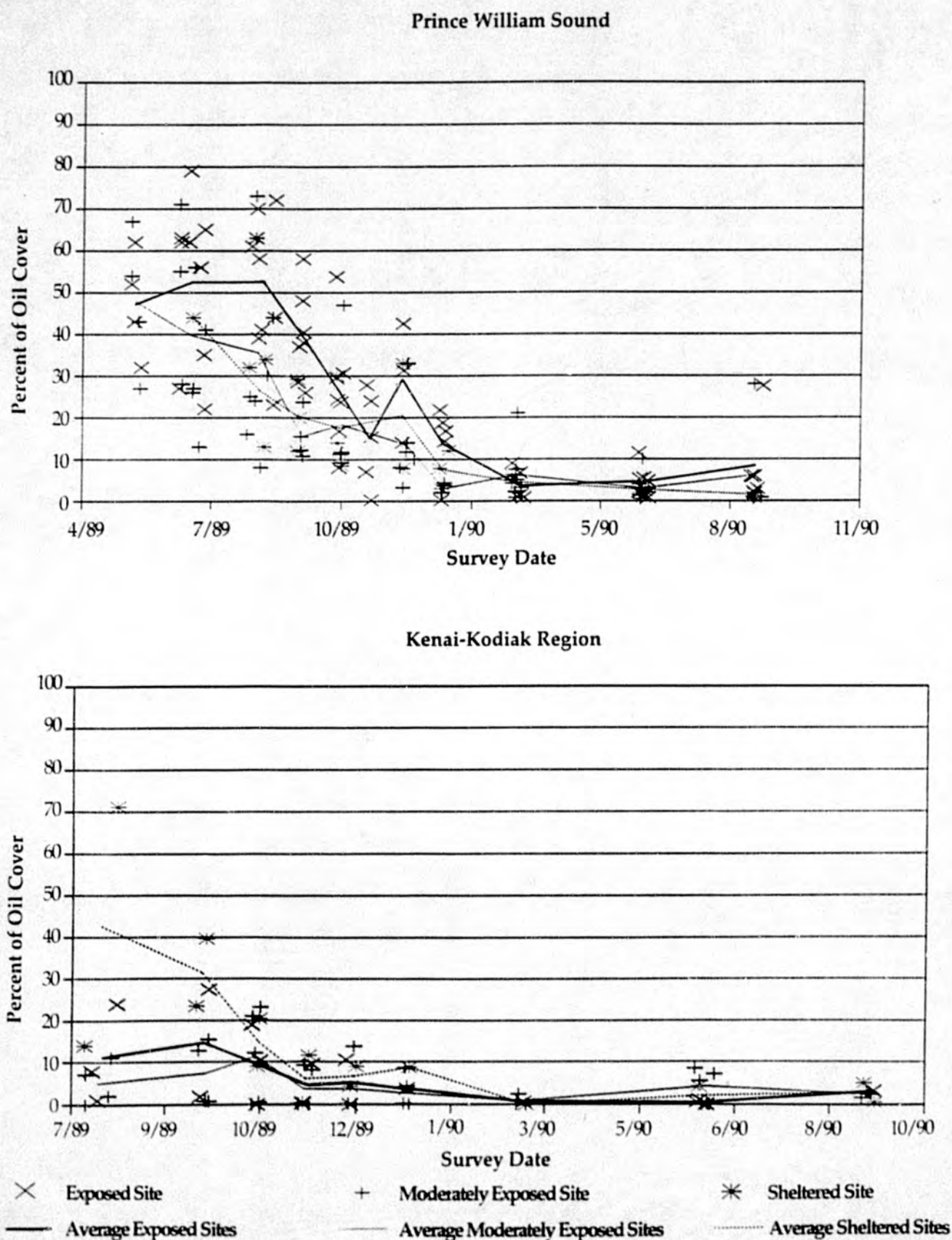
SITE	5/89	6-7/89	8/89	9/89	10/89	11/89	12/89	1/90	3/90	6/90	9/90
AP-1	-	79		28	29		14	-		2	2
AP-2	-	62		38	54		42	22		11	6
AP-3	32	22		26	-		-	-		-	-
AP-4	-	-		29	30		33	12		2	2
AP-5	43	41		-	11		8	-		1	-
AP-6	-	-		12	8		-	8		4	1
AP-7	-	13		11	11		-	4		2	-
AP-8	-	56		40	24		-	14		5	6
AP-9	-	65		-	-		-	-		-	-
AP-10	-	35		37	24		-	19		5	3
AP-11	43	63		48	17		-	-		1	-
AP-12	62	62		58	31		31	17		5	27
AP-13E	54	55		-	-		14	-		3	1
AP-13C	67	71		-	47		33	-		10	28
AP-13W	52	27		-	8		-	0		1	6
AP-14	27	28		24	-		12	4		3	0
AP-15	-	56		-	-		-	-		3	1
AP-16	-	27		12	9		10	2		1	1
AP-17	-	26		15	12		3	2		0	-
AP-18	-	44		20	14		8	3		2	2
AH-1	-	1		2	0		0	-		0	-
AH-2	-	14		23	9		4	-		0	0
AH-3	-	0		1	0		0	0		0	-
AH-4	-	7		13	21		0	0		0	-
AK-1	-	-		40	20		9	9		4	5
AK-2	-	2		1	0		0	0		0	-
AK-3	-	-		15	23		-	4		5	3
AK-4	-	-		27	10		-	4		1	-
AK-5	-	8		-	19		10	-		1	3
AS-1	-	-		-	12		14	9		8	1

Note: Site AP-13 was subdivided into three sections (East, Central and West) but is considered as a "single" site in most instances.

- Site not visited.

* Site visited but no measurement taken.

Figure 5
Surface Oil Cover Versus Time



20 percent of the original length of oiled shorelines in the Sound. Furthermore, band width alone does not take into account variations of the initial severity of oiling. Other factors related to the degree of initial oiling include oil thickness, depth of penetration, patchiness, and viscosity. However, the data set represents those areas that were most heavily oiled and where oiling was expected to persist longest. Therefore, the data set presents a bias toward worse-case conditions.

Field surveys in the summer of 1989 support the generalization that oil was scattered and generally light in the Kenai-Kodiak region. The oil bands at AK-4 and AK-5 were both wide initially, but on these large beaches the initial average oil cover values were artificially low because of the extensive proportion of unoiled surface material surveyed in the middle and lower intertidal zones. If one looks only at the oiled areas of these two beaches rather than the total observed areas, the original oil cover values were reduced from 100 to 7 percent by January 1990 at AK-4 and to 0.7 percent by March 1990 at AK-5, so the average values in Table 6 do reflect a real change (Table D-2, on page D-3).

Oil Cover Maps

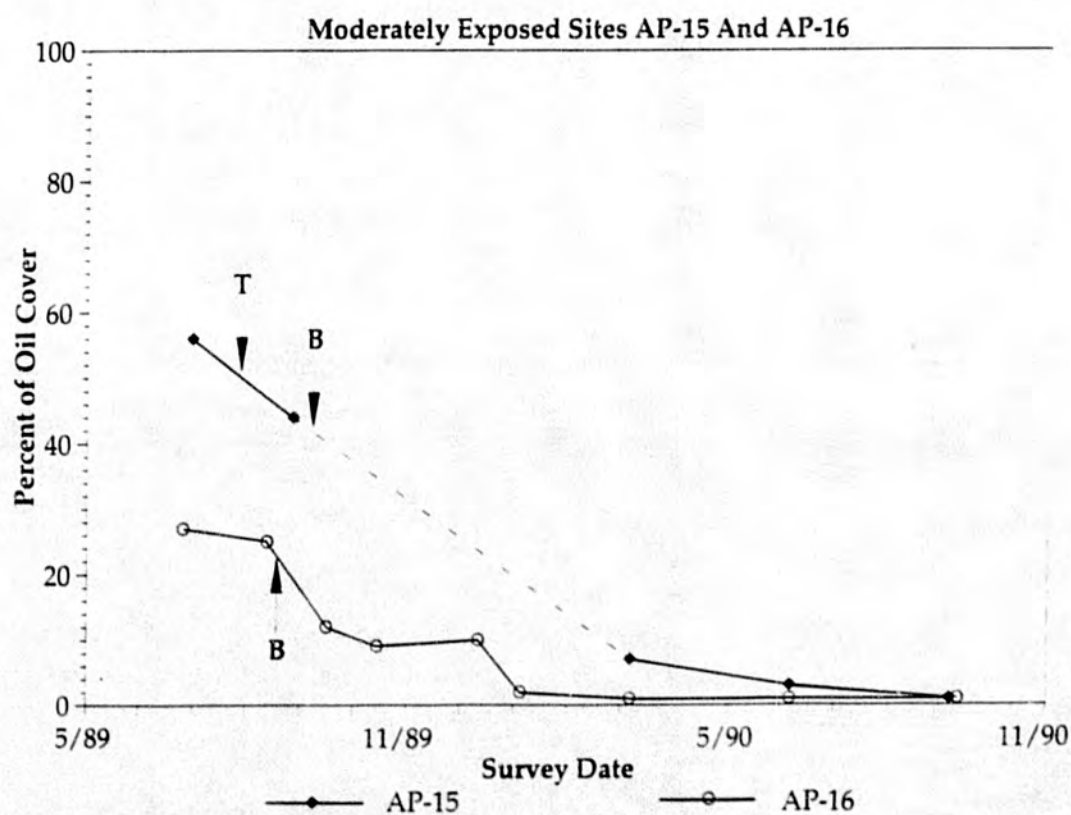
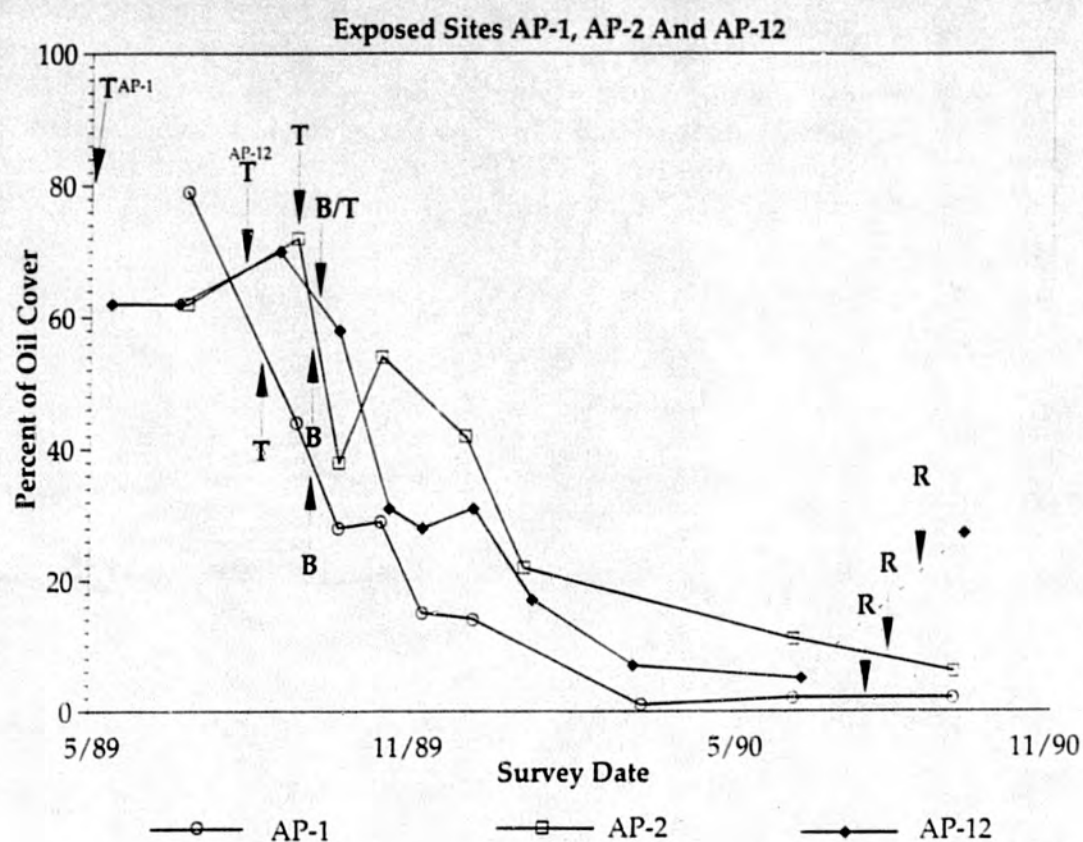
The changes in the distribution of surface oil cover through time are illustrated in a selected set of maps (Appendix D). Criteria for the selection are:

- Prince William Sound
 - Two data sets from each of the exposed, moderately exposed, and sheltered sites in the Sound; these two sets would represent the greatest and least surface cover at the time of the March 1990 (end of winter) survey.
- Kenai-Kodiak Region
 - Three sites from the Kenai-Kodiak region that represent the range of wave-energy environments and that initially had an extensive surface oil cover.
- General
 - Individual maps from the time series at each site that represent a significant change or that illustrate a trend.

Changes in percent of surface oil cover, relative to observation area, are obtained by comparing only the area of beach repeatedly documented by all surveys. Figure 6, on the next two pages, shows that Prince William Sound sites and Kenai-Kodiak sites had major reductions of surface oiling following summer 1989.

Data for each of the sites and the treatment activities that took place during 1989 are summarized in Table 7a, on page 26, and Table 7b, on page 27. Representative maps for each site illustrate the major changes that took place in the distribution of oil on the beaches (Appendix D). The changes are summarized in a set of graphs (Figure 6, on the next two pages) based on an analysis of oil cover transect data.

Figure 6
Transect Surface Oil Cover Changes Over Time

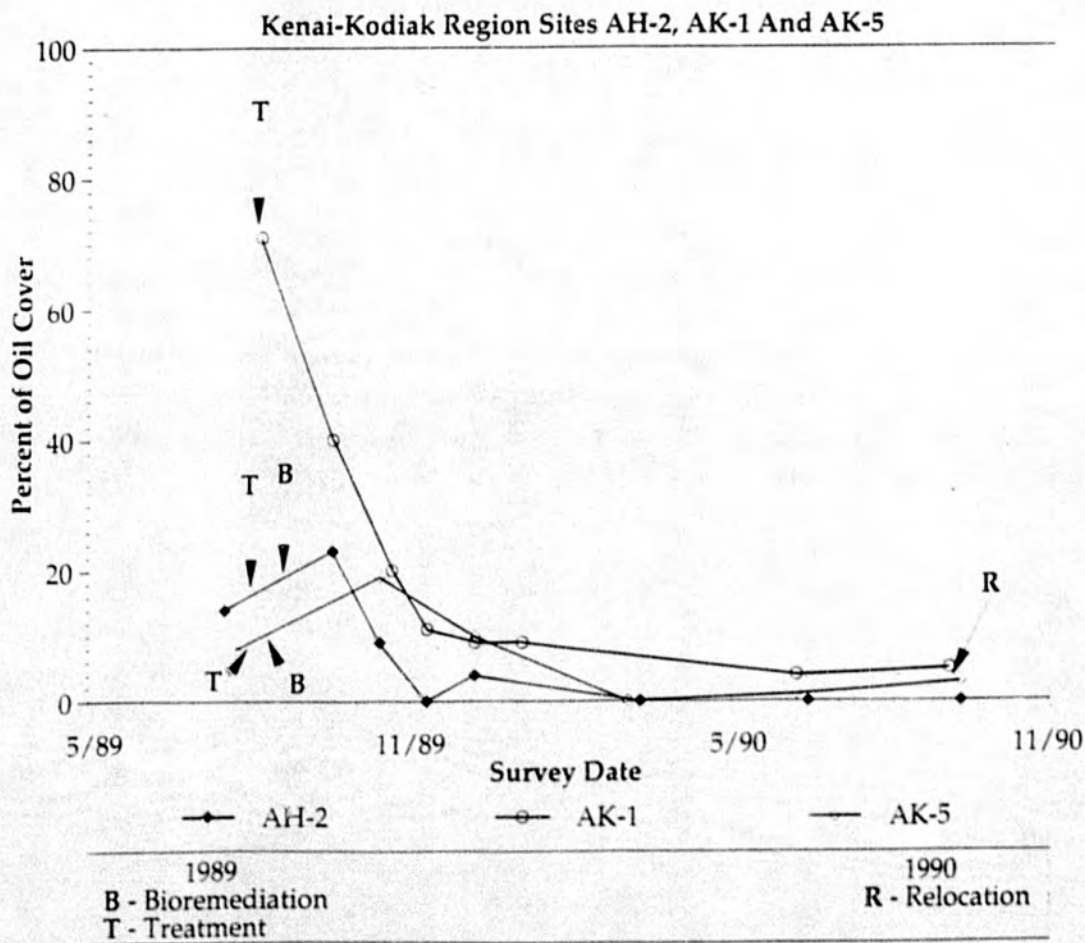
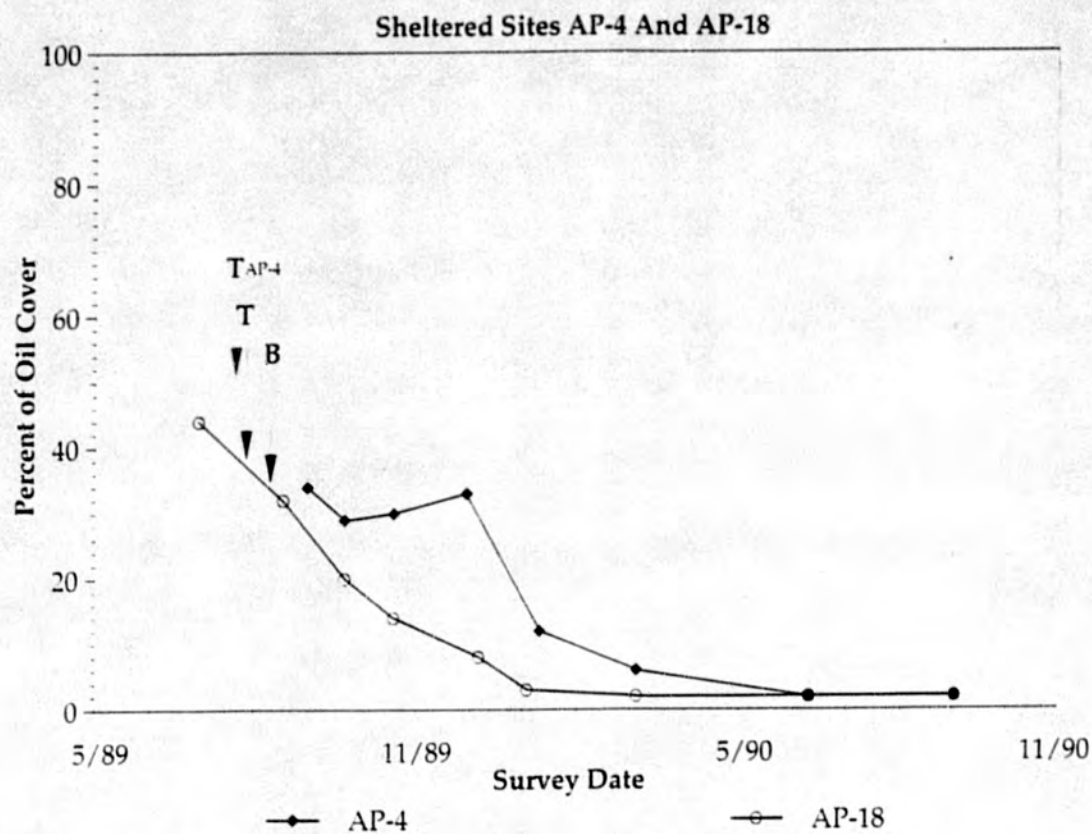


1989
 B - Bioremediation
 T - Treatment

1990
 R - Relocation

--- Interpolated Data

Figure 6
Transect Surface Oil Cover Changes Over Time / Continued



Ten sites were selected to illustrate changes in the distribution of surface oil cover through time. Site characteristics are shown in Table 7a and treatment histories in Table 7b, on page 27.

Table 7a
Selected Study Sites/General Characteristics

Site	Wave-Energy Environment	Initial Oiling Category	Initial Oiled Area (m ²)	Summer 1990 Oiled Area (m ²)
AP-1 Northeast Smith Island	Exposed	Wide	1,565	40*
AP-2 Northwest Smith Island	Exposed	Wide	1,073	97*
AP-12 Northeast Latouche Island-North	Exposed	Wide	2,037	204*
AP-15 North Evans Island	Moderate	Wide	605	6*
AP-16 Southwest Elrington Island-East	Moderate	Medium	411	11*
AP-4 Foul Pass, Ingot Island	Moderate	Wide	507	27*
AP-18 Southwest Elrington Island-Southwest	Sheltered	Medium	690	28*
AH-2 North Windy Bay	Sheltered	Medium	614	1*
AK-1 Perevalnie Point	Sheltered	Wide	366	37*
AK-5 Ushagat Island	Exposed	Wide	451	27*

*—September 1990 survey data

—June 1990 survey data (prior to sediment relocation)

The maps shown in Appendix D are a product of transect data. An important feature of the monitoring program was that each site had multiple transect lines across the beach. Owens and Teal (1990b) have shown that single transects have limited value because there is considerable alongshore variability in the distribution of oil on most beaches.

The data in Table 6 were obtained by dividing the actual observed oil cover by the total observed area at each site. The total observed area varied from survey to survey because of daily and monthly differences in the height of the low tides at the time of each survey, and because of snow on the upper beach in winter (particularly during the January and March 1990 surveys). In contrast, the data in Figure 6 reflect only that part of the beach that was common to all surveys.

Specific Results

Prince William Sound Exposed Environments

The examples of exposed sites (AP-1 and AP-12) were initially heavily oiled both in terms of oil coverage and of oil concentration, with the northeast Smith Island site (AP-1) being among the most oiled in the Sound. Changes in beach morphology at these sites are discussed on page 17.

Selected study sites were grouped by similarities, as shown by the line divisions in this table.

Table 7b
Selected Study Sites/1989 Treatment Histories

Exposed Sites in Prince William Sound

- | | |
|-------|---|
| AP-1 | 1. Cold water deluge and wash in late April/early May 1989
2. Deluge and warm water wash completed on Aug. 13, 1989
3. Bioremediation on Sept. 8 and 12, 1989 |
| AP-2 | 1. Deluge and warm water wash in late August and early September 1989
2. Bioremediation on Sept. 8, 11 and 12, 1989 |
| AP-12 | 1. Deluge and warm water wash in August and September 1989
2. Bioremediation on Sept. 14, 1989 |

Moderately Exposed Sites in Prince William Sound

- | | |
|-------|--|
| AP-15 | 1. Warm water flush by MAXI barge on July 20-23, 1989
2. Manual removal of oiled debris and hand wiping on July 20-23, 1989
3. Bioremediation on Sept. 9, 1989 |
| AP-16 | 1. Bioremediation on Aug. 16, 1989 |

Sheltered to Moderately Exposed Sites in Prince William Sound

- | | |
|-------|--|
| AP-4 | 1. Warm water flush by MAXI barge on July 24-30, 1989 |
| AP-18 | 1. Manual removal of oiled debris (Summer 1989)
2. Bioremediation on Aug. 6, 1989 |

Kenai-Kodiak Region Sites

- | | |
|------|---|
| AH-2 | 1. Manual pickup in August 1989
2. Bioremediation on Aug. 15, 1989 |
| AK-1 | 1. Manual pickup of surface oil and hot water washing (Summer 1989) |
| AK-5 | 1. Manual pickup July 25 to Aug. 12, 1989
2. Bioremediation on Aug. 12, 1989 |

The timing of some of the observed changes at these locations reflects the treatment activity schedule. For example, AP-1 initially had a 100 percent oil cover in the intertidal zone and was treated by cold-water washing in April 1989 before the first survey, and by warm water washing in August 1989 before the second survey. The oil cover map (Figure D-1, on page D-4) reflects these activities: Oil cover on this beach dropped from an average value of 79 percent before the August treatment to 44 percent in the post-treatment survey due to a combination of treatment and late August storms (Table 6 and Figure 6). Fluctuations of oil cover at AP-1 during the early summer of 1989 could have been the result of "free" oil from within the porous beach being re-stranded on the beach surface. Following these summer 1989 reductions, surface oiling at AP-1 was further reduced by wave action (Photographs B-5 through B-10, on pages

B-3 and B-4). Two major storms, in mid-October 1989 and early November 1989, coincided with high spring tides to produce waves capable of reworking sediments on the upper beach so that by the time of a site visit on Nov. 20, 1989 the intertidal zone was essentially free of surface and subsurface oil.

In contrast to AP-1, a similarly oiled site (AP-12) was not treated until August 1989 when the central and western segments were washed. The eastern segment was washed in September, and then the entire beach was bioremediated on Sept. 14, 1989. The surface maps and oil cover data from this site show virtually no significant reductions through Sept. 19, but the average dropped over a four-week period from 58 percent on Sept. 19 to 31 percent by Oct. 20, 1989 (Figure D-3, on page D-6; and Table 6). This sharp reduction, which is mirrored in the detailed transect analysis (Figure 6), was a result of the combined effects of the treatment activities and of two major winter storms that passed through the region during Oct. 4-8 and 15-21, 1989. Both storms had peak winds over 85 km per hour (hr), and the second had sustained average winds greater than 50 km/hr out of the easterly directions for four days, at a time of high spring tides (Appendix E). A time-lapse camera was installed on the adjacent AP-13 site, and between Nov. 11, 1989 and April 12, 1990, breaking wave heights of greater than 0.5 m were observed during daylight hours on a total of 20 days (Appendix F). By June 1990, only a very narrow strip of oil-coated or oil-stained sediments was left on the surface at the highest parts of the beach at AP-12, which is reworked only by high waves during spring tides.

At both AP-1 and AP-12, winter wave action was not able to reach oil deposited during high spring tides above the normal high water level. During the 1990 summer cleanup program, these residual oiled sediments in the storm berms were mechanically relocated across the beach and spread over the upper intertidal zone, where loose oil was picked up manually; the oil-coated sediments were left to be reworked and redistributed by wave action. At AP-12, this activity occurred immediately before the September 1990 site visit, and that survey accurately reflects an increase in the surface oil cover from 5 percent in June before the treatment to 27 percent in September.

Prince William Sound Moderately Exposed Sites

The first example in this category is provided by a small pocket beach, part of a tombolo, located on the northwest coast of Evans Island (AP-15) (Figure A-5, on page A-6). The predominantly granular beach is partially exposed to waves generated in Knight Island Passage. Treatment of the beach at this site by washing before the August 1989 survey reduced the total surface oil cover by about 20 percent, but the beach still had patches of greater than 50 percent cover throughout the intertidal zone (Figure D-4, on page D-7). No surveys were conducted during the winter due to access difficulties, but by March 1990, the winter wave action, probably

augmented by late-summer 1989 bioremediation, had reduced the oil cover to some patches on the northern end of the study site. By June 1990, these patches had been reduced even further; and by September 1990, the surface oil cover was 1 percent, indicating that spring-summer wave action played an important role in natural surface cleaning on this moderately exposed beach.

The second example in this category is provided by a 180-meter-long, low-angle beach at the south end of Elrington Passage (AP-16) (Figure A-6, on page A-7). The beach is composed of granules, pebbles, and cobbles and is protected from all directions except to the northeast. The site was not extensively oiled to begin with, and was treated only with bioremediation on Aug. 16, 1989. Data from the two pretreatment surveys (June 27 and Aug. 10, 1989) indicate that little oil removal had occurred over that six-week period. By contrast, the Sept. 18, 1989 survey indicated that the oil cover was reduced by half (Table 6). The detailed transect analysis shows a similar change (Figure 6). This was a period of very little storm activity so the change is likely attributable to a combination of abrasion and washing by small breaking waves and the bioremediation treatment. Winter wave action continued the cleaning process so that by March 1990 only scattered patches of oil-stained sediments remained, generally in the upper intertidal zone (Figure D-5, on page D-8).

Prince William Sound Sheltered Sites

The first example in the sheltered category is provided by a beach located between Ingot and Disk Islands (Figure A-2, on page A-3). The Ingot Island study site (AP-4) is on a cusped spit where beach sediments consist of poorly sorted granules, pebbles, and cobbles. The site was treated by washing before the first survey (Aug. 22, 1989), but a wide band of oil remained along the upper beach (Figure D-2, on page D-5). This cover was largely unmodified through December 1989 (Figure 6) despite breaker heights of more than 1 m on Nov. 22. The change between the December and January surveys is dramatic. During that four-week period, two major storms (Dec. 11-12 and 27-31) generated dominant winds out of the southeast, with peak wind speeds greater than 110 km/hr. Spring high tides occurred at the same time as these storms. These winds and resultant waves coincided with the narrow fetch window at this site and reworked, washed, and abraded the oiled sediments. Time-lapse photography of the southern half of this site recorded 25-centimeter waves or larger on six days during December (2-3; 10-12; 27) that were coincident with easterly or southeasterly winds (Appendix E). Site AP-4 also appears to have been exposed to, and influenced by, strong northerly winds. Reduction of surface oil cover occurred on the northern side of the spit in response to these storms, as indicated by field observations during December 1989/January 1990. Some further cleaning took place over the remaining winter months, but well over three-quarters of the change that was recorded between August 1989 and March 1990 occurred between the December and January surveys.

A second sample of a sheltered site is provided by the south Elrington Island site (AP-18). This beach is located on the east side of a cove, along a narrow stretch of shore separating the cove from north Twin Bay (Figure A-6, on page A-7). This protected beach is formed of cobbles, sand, and pebbles. Oil cover reduction at site AP-18 occurred earlier than at AP-4, with most reduction taking place between the June and August 1989 surveys (Figure 6). The site was bioremediated on Aug. 6, but it is unlikely that all the reductions recorded by Aug. 9 reflect this treatment because insufficient time had elapsed for the biological process to be effective. The changes between the August and September 1989 surveys were not large, but a second period of major change took place between Sept. 17 and Oct. 16, 1989. The transect analysis from that period shows that the oil cover was halved (Figure D-6, on page D-9). The two major storms that occurred on Oct. 4-8 and 15-21, 1989 may have caused this change. The latter storm was a particularly important event because it coincided with one of the highest spring tides of the year (Table F-1, on page F-2).

Kenai-Kodiak Region Trends

Three sites in the Kenai-Kodiak region illustrate very different situations from the Sound sites. The exposed Ushagat Island site (AK-5) had an initial wide band of oil on the beach. The low total oil cover for this site indicates that most of the beach was not oiled. A better measure of the amount of change at this location is to compare the values for the actual oiled area, rather than use a fraction or percent value for the entire beach. The surface oil cover doubled between late July and October 1989 because wave action distributed the original stranded oil over higher parts of the beach. By December 1989, winter wave action reduced the oiled area to about the original cover. The beach had little surface oil cover remaining by June 1990, but the beach transect data (Appendix C) indicated that some burial had occurred. A survey of the site in June 1990 showed that the reduction of the oil cover over the winter months was a result of erosion of beach material in the northern half of the study site and burial of oiled sediments in the southern half. This site is one of the few where large-scale burial of oiled sediments was found by the regional ground surveys. Cross-beach trenches cut by a power shovel showed that the distribution of the buried layer in June 1990 corresponds to the surface oil cover map for December 1989. Relocation work in early September 1990, to expose the oil that had been buried on the berm, was followed by a site survey that showed the surface oil cover increased to 3 percent from 1 percent in June of that year.

The north Windy Bay site (AH-2) is a sheltered, long, and low-angle site located in a pocket cove (Figure A-7, on page A-8). Sediments on this beach consist of gravel, sand, and mud. This sheltered location had a 3- to 6-meter-wide band of oil stranded on the upper beach at the time of the

first survey in July 1989. Manual pickup had taken place before the first survey. Wave action was effective at this site in further cleaning the beach, and no surface oil remained by the March 1990 survey. The beach profile had not changed significantly through time, so it is unlikely oil was buried.

A wide band of oil stranded at Perevalnie Point (AK-1) was removed by manual pickup and washing, leaving only oil-coated and oil-stained sediment by the September 1989 survey. The site is a low-angle, cobble and gravel beach located in a small cove between steep, rocky outcrops. Bedrock underlies the thin beach cover at this site. Low wave energy characterizes this shoreline because the site is protected from the Gulf of Alaska by the Perevalnie Islands (Figure A-8, on page A-9). Some natural cleaning occurred between the September and November 1989 surveys, but no subsequent changes were noted, although the amount of remaining oil was small.

Sites With Berm Sediment Relocation Treatment in 1990

Evaluation of the SSAT survey results indicated that oil remained on some beach berms in the spring of 1990 above the normal high-water level (in the supratidal zone) and had not been reached by winter wave action. A treatment technique for this type of situation was developed that involved relocating that material downslope into the upper intertidal zone to accelerate the natural cleaning processes. Once relocated, any free oil was picked up manually or by using sorbent materials, and the remaining oil was then to be abraded, reworked, and dispersed by waves through the summer and, particularly, the 1990-91 winter months. Bioremediation was carried out after relocation to enhance degradation of the residual oil by native bacteria. The SSAT survey also defined a few areas of subsurface oil that had not been reworked by winter wave action. For these latter situations, a tilling approach was recommended, in which the subsurface oil was brought to the surface and exposed to wave action and biodegradation.

Comparison of surface oil cover observations made before and after the treatment activities at the sites indicates a considerable reduction in the occurrence of residual oil in the supratidal zone. Of the 26 sites with observations before and after berm relocation, the number with a wide or moderate oil cover in the upper intertidal zone was reduced from 19 to eight and, significantly, the number of sites with a wide or moderate cover in the supratidal zone was reduced from eight to one (Table 8, on the next page). An expected consequence of the relocation and tilling was a temporary increase in surface oil cover in the upper intertidal zone at some sites (for example, at AP-12, AP-13C/W, AK-1, and AK-5, as shown in Table 6). Summer wave action was observed to have reworked and redistributed sediments on exposed beaches; however, the greatest changes were expected to have occurred over the 1990-91 winter months.

After berm relocation, only nine of 26 sites still had a wide or moderate cover in August/September 1990.

Table 8
Changes in Oil Cover by Tidal Zone and
Oil Category/26 Berm Sediment Relocation Sites

		Supratidal Zone		Upper Intertidal Zone	
		Pre-Treatment	Post-Treatment	Pre-Treatment	Post-Treatment
Oil Cover Category	Wide, Heavy	5	0	14	2
	Moderate	3	1	5	6
	Narrow	2	2	4	6
	Very Light	1	5	2	9
	No Oil	15	18	1	3

Discussion - Rates of Change

All of the field observations, maps, and transect analyses show that significant reductions in surface oil cover occurred during the 1-1/2 years after the spill. By September 1990, eight of the 26 sites had no surface oil, and a further 16 sites had a 5 percent or less cover. The oil that remained after the winter was located, for the most part, on the highest sections of the beach, above the limit of normal wave action. This zone is reworked only during periods of spring high tides or by major storm waves, and the residual oiled sediments were moved across the beach where they could be reworked by waves. Surface relocation treatment resulted in increased surface oil cover values at five sites because of sediment relocation before the September 1990 surveys.

The results of the 1989 summer treatment program are evident at most locations. The effects of treatment are probably underestimated by the surface oil cover data because this approach does not take into account reductions in the oil thickness and oil-in-sediment concentrations. The role of winter wave action is clearly demonstrated as the slower rates of change from January 1990 onward coincide with the relatively calmer wind and wave conditions experienced over that period at most sites, in marked contrast to the more energetic period from September to the end of December 1989. This change in rates of removal also occurs, in part, because the oil that was more easily removed had been mechanically removed by wave action by the end of December, so less oil was available to be removed.

Rates of natural cleaning by weathering would be expected to vary considerably from site to site and from year to year, depending primarily on the coincidence of winds and waves with the fetch window for a given site. The rate of change also varies within a single beach system. The latter is evident from inspection of the maps in Appendix D.

The variability from one location to another is often due to subtle changes in the local coastal environment. Three adjacent sites on northern Smith Island are compared to illustrate this point. The three sites are similar in character and have the same exposure in terms of fetch distances, but each is

affected differently by storm winds because of their different beach orientations (Figure A-1, on page A-2). The comparison addresses the reduction of the area of surface oil cover and relates changes to both treatment history and occurrence of onshore storm winds (Figure 7, on the next page). For ease of comparison, rates of change as shown in Figure 7 are normalized to the initial equivalent oiled area, which is taken as 100 percent. The following discussion is based on the raw data shown in Table 6, on page 21.

Northeast Smith Island (AP-1)

This beach is exposed to storms out of the northwest through northeast directions. The sequence of changes in the surface oil cover is:

- Original oil cover (April 1989) was 100 percent in the intertidal zone, which is equal to approximately 80 percent of the total surveyed area.
- Most of the surface changes occurred prior to Sept. 16, 1989, following two periods of extensive treatment (Table 7b), by which time oil remained on only 28 percent of the surveyed area because of treatment and summer wave action.
- Virtually no change occurred between Sept. 16 and Oct. 15, 1989, during which there were no storm winds out of the north or northeast.
- Further reduction of surface oil cover to 15 percent occurred by Nov. 10, 1989 following storm winds out of the north on the two previous days and during Oct. 16-21; the October storm may have been the more important because it coincided with very high spring tides.
- Reduction to 1 percent occurred by March 1990, with 10 storm events out of the northwest and north during that interval.

The AP-1 site was affected by three major storms and four additional storms with onshore winds between mid-October 1989 and early June 1990 (Photographs B-5 through B-10, on pages B-3 and B-4). The effects of the two periods of extensive treatment activity, followed by strong storm-wave activity during the early winter, are considered to be the primary causes of the initial lowering of the quantity of oil on the beach.

Northwest Smith Island (AP-2)

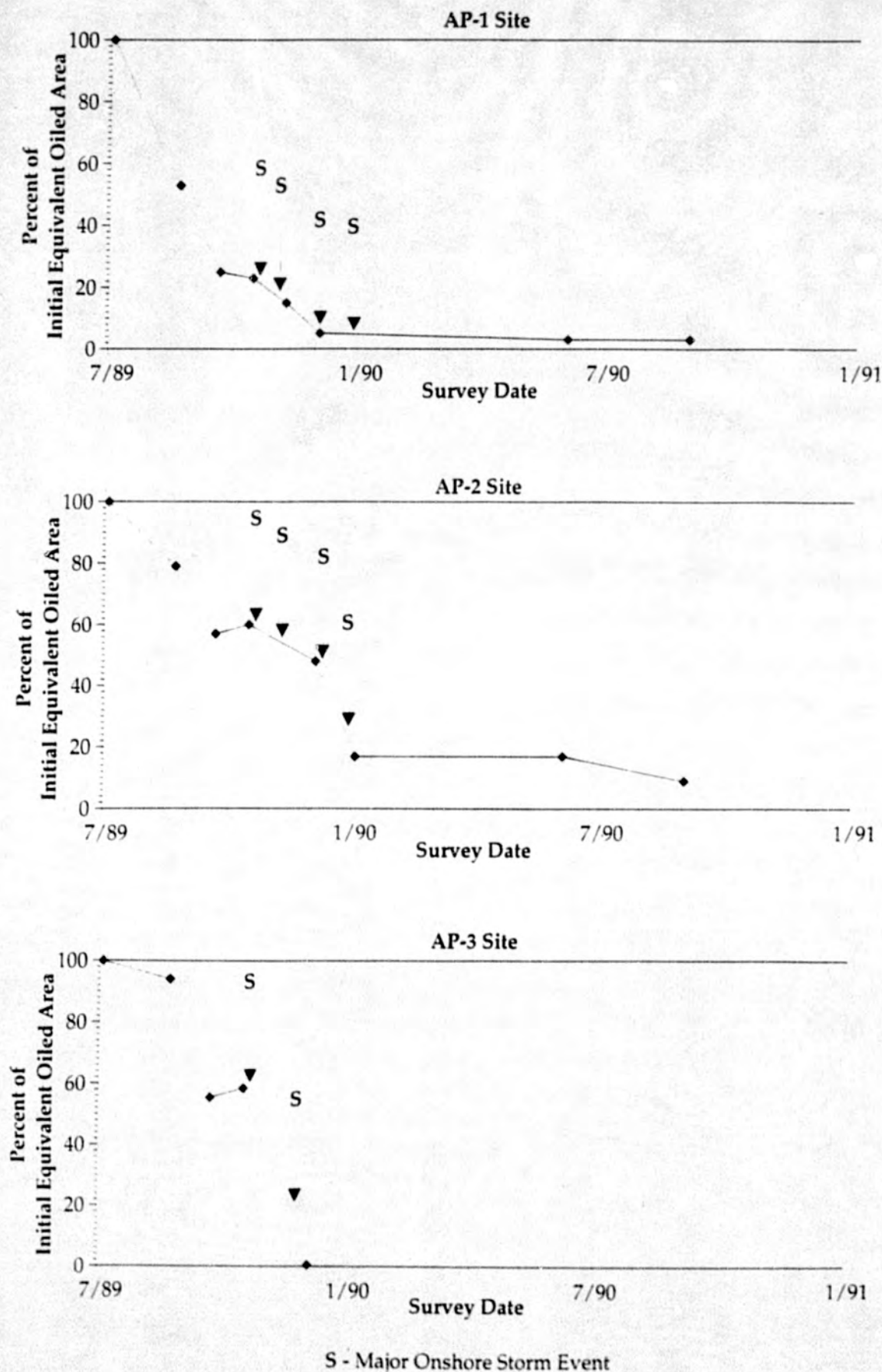
Although oriented east-west, this beach is partially sheltered to the northeast and is exposed to storms only out of the northwest to north window. The pattern of change at this location is as follows:

- The beach had a complete (100 percent) oil cover in April 1989.

Figure 7, on the next page, shows the percentage of surface oil remaining at Smith Island sites AP-1, AP-2, and AP-3. Major storm events affecting these sites produced large waves that reworked, abraded, and washed surface sediments.

Figure 7

Smith Island Surface Oil Changes Over Time/Initial Oil Taken as 100 Percent



- Treatment activities reduced the area of surface oil cover to 38 percent by the time of the Sept. 20, 1989 survey.
- No reduction took place between Sept. 20 and Oct. 14, 1989 (Table D-2, on page D-3), during which period there were no storm winds out of the north or northwest.
- Surface oil cover was reduced from 54 percent on Oct. 14, 1989 to 42 percent by the Dec. 4, 1989 survey, probably as a result of storms out of the north in mid-October and early November 1989.
- A major reduction to 22 percent happened between Dec. 4, 1989 and Jan. 2, 1990, associated with strong onshore storm winds out of the northwest during Dec. 30-31.
- No further reduction of the oiled area occurred between Jan. 2 and June 5, 1990 (Table D-2, on page D-3), during which period six secondary storms with strong onshore winds affected this site.

The surface oil cover on AP-2 was not removed as much as the surface oil cover at the two other sites in this comparison, although the site was subject to three major storms and several additional onshore storms. The major onshore storms mechanically worked the beach sediments and reduced the surface oil cover from 54 to 22 percent. Most of the post-treatment change at this site, however, can be related to the December 1989 storm events. The subsequent secondary storms caused no further change, probably because the wave washing and abrasion were less effective at removing weathered oil. The slower reduction in the surface oil cover is attributed to the limited level of treatment in comparison to AP-1 during 1989, and to shoreline orientation, which sheltered the beach from direct wave action out of the east and northeast during the early winter storms.

Northeast Little Smith Island (AP-3)

The final beach in this comparison faces the northeast and is exposed to storms out of the north through to the east. Changes at this location were:

- The treatment program and summer wave action reduced surface oil cover to 55 percent of the original (May 1989) oiled area (Table D-2, on page D-3).
- Little change took place between Aug. 28 and Sept. 21, 1989, during which there were no storm winds out of the north or northeast.
- All remaining oil was removed between Sept. 21 and Nov. 11, 1989 as a result of two major onshore storms; one out of the north-northeast on Oct. 15-21, coincident with spring tides, and a second storm out of the north on Nov. 6-10.

The AP-3 site was cleaned by a combination of the treatment activities followed by two major onshore storms that occurred relatively early in winter 1989-90. Shoreline orientation and the exposure of this beach to east and northeast storms are considered to be the primary causes for the rapid cleaning at this site.

Discussion - Cleaning Processes

The difference between the rates of natural cleaning at the three exposed and adjacent Sound sites (AP-1, AP-2, and AP-3), and at the two sheltered Kenai-Kodiak sites (AH-2 and AK-1) illustrates that exposed, moderate and sheltered wave-energy categorizations oversimplify the complexity of the processes that operate in the coastal system. The three Smith Island sites are all north-facing, but rates of change during the winter were induced by storm waves out of specific directions. Similarly, adjacent sites AP-11 and AP-12 on northeast Latouche Island were also cleaned at different rates during the winter because of different shoreline orientations. The east-facing AP-11 beach was not treated during 1989 but was almost oil free by mid-November 1989 after a succession of five onshore storms during early winter. In the case of the sheltered, low to moderate wave-energy AP-4 site in the Sound, this beach was largely cleaned by two major storm events during which wind speeds in excess of 110 km/hr were aligned with the narrow fetch window for that location. One of these storms was the strongest event of the winter in the Sound. Natural cleaning rates were clearly sensitive to shoreline orientation and exposure. It is evident that the mechanical work produced by wave action on a beach can play a critical role in removal, transport, and weathering of oiled sediments. In addition, fine sediments are more easily entrained than coarse material and can be an effective abrasive tool, even on moderately exposed or sheltered beaches.

This cleaning action is also very dependent on the character of the stranded oil. Wave abrasion and cleaning are more effective on the lighter hydrocarbon compounds than on weathered oil; therefore, natural cleaning rates would be expected to be greatest when waves directly rework beach sediments at an early stage relative to initial oil stranding. In this respect, the observed cleaning rates of the spill could easily have differed because of the variability of storm wave intensity, coincidence of storms and spring tides, wind and wave directions, and timing of oil stranding relative to the winter storm season.

The natural cleaning of oiled shorelines results from a range of physical, chemical and biological processes that contribute to different degrees and that operate on different time scales. Immediately following a spill, the most important processes are spreading and evaporation. Once oil has become stranded, wave abrasion, washing, and flushing are the primary removal processes. During the summer of 1989, the Exxon flood-and-flush treatment program, as well as natural wave washing and

flushing, resulted in the removal of most of the free or mobile oil from the shorelines of Prince William Sound. Further removal occurred over the winter months by storm-wave abrasion and washing so that by mid-winter, the oil that remained was primarily as coats or stains.

Natural biodegradation of oil residues is a significant process after wave action or washing has removed the thick oil deposits. This weathering process was enhanced, following large-scale field trials in 1989, by the addition of fertilizers to areas where oil-coated or oil-stained material was present. This bioremediation technique is thought to have increased rates of natural bacterial degradation of oil by a factor of five (Prince, Clark, and Lindstrom 1990). During the 1990 treatment operations, at sites designated for bioremediation, the fertilizers were added on a regular basis to provide a continuing source of nutrients for the oil-degrading bacteria.

The set of long-term monitoring sites does not include a location that is representative of sheltered bedrock outcrops. Regular visits to sections of coast in Northwest Bay and Upper Passage that contained this shoreline type indicated that by January 1990 there had been a significant reduction of the oil cover on bedrock outcrops and boulders. In many sections the intertidal oil had been removed completely, even in very sheltered areas where wave action would not have been a factor in natural cleaning. A laboratory study by Exxon Production Research Company, using oiled material collected from northeast Smith Island and from Meares Point on Perry Island, showed that the residual oil was associated with large amounts of very fine sediment particles (silts and clays) (Bragg et al. 1990). Fine sediments are common in the waters of Prince William Sound because "glacial flour" is carried by streams that originate in the ice fields of the hinterland. Simulated tidal action resulted in a flocculation-like process that formed clay-oil aggregates, which detached from the oil on the pebbles or cobbles (Jahns et al. 1991).

The process by which the particles interact with the residual oil and seawater to form the clay-oil aggregates may have been responsible for oil removal on many sheltered sections of coast in the Sound. The washing and removal of most of the oil by the summer treatment activities left a relatively thin oil coat or stain on bedrock and boulder surfaces and made possible this secondary natural cleaning process. This process, combined with photodegradation and dispersion, also significantly increases the oil-water interface and thereby makes the residual oil readily available for biodegradation. Although the process is relatively minor when compared to the volume of oil removed from the shorelines by the washing and flushing activities, the removal of the thin residue contributed to the natural cleaning of the shorelines.

Observations during the spring 1990 SSAT survey identified some residual oil at a few sites on the highest parts of the beach that had not been reworked and cleaned by winter wave action. This oil had been deposited in the supratidal zone either by spring tides or by storm waves and was beyond the reach of most wave activity. In order to expedite the natural cleaning of these oiled sediments, a program of sediment relocation was

developed which involved movement of the material from the supratidal beach into the the upper intertidal zone, where it could be abraded and washed by waves.

The combination of treatment activities and natural cleaning is documented by the observations and data from the study sites and by site visits elsewhere in Prince William Sound and the Kenai-Kodiak region. The picture that emerged in the spring of 1990 was one of basically clean shorelines with residues where wave action and Exxon's activities had not been able to reach the oil. Although the cleaning processes involved different mechanisms and operated on different time scales, the net effect was that most of the oil was removed from the shorelines within a year after the spill.

Subsurface Oil Conditions

By their very nature, subsurface oiling conditions are difficult to characterize and to monitor over time. Observations were made at each study site along a transect to describe the presence and type of any oil below the beach surface. This information is supplemented by observations from pits dug as part of other programs. Many of these observations were made during the joint regional surveys. The trends that have emerged, and that are summarized in the next few paragraphs, therefore represent a compilation of various data sources with examples selected to illustrate the major findings. The overall conclusion is that subsurface oil was not a common occurrence in 1990. Where subsurface oil had been identified during 1989 surveys, little remained by the end of 1990.

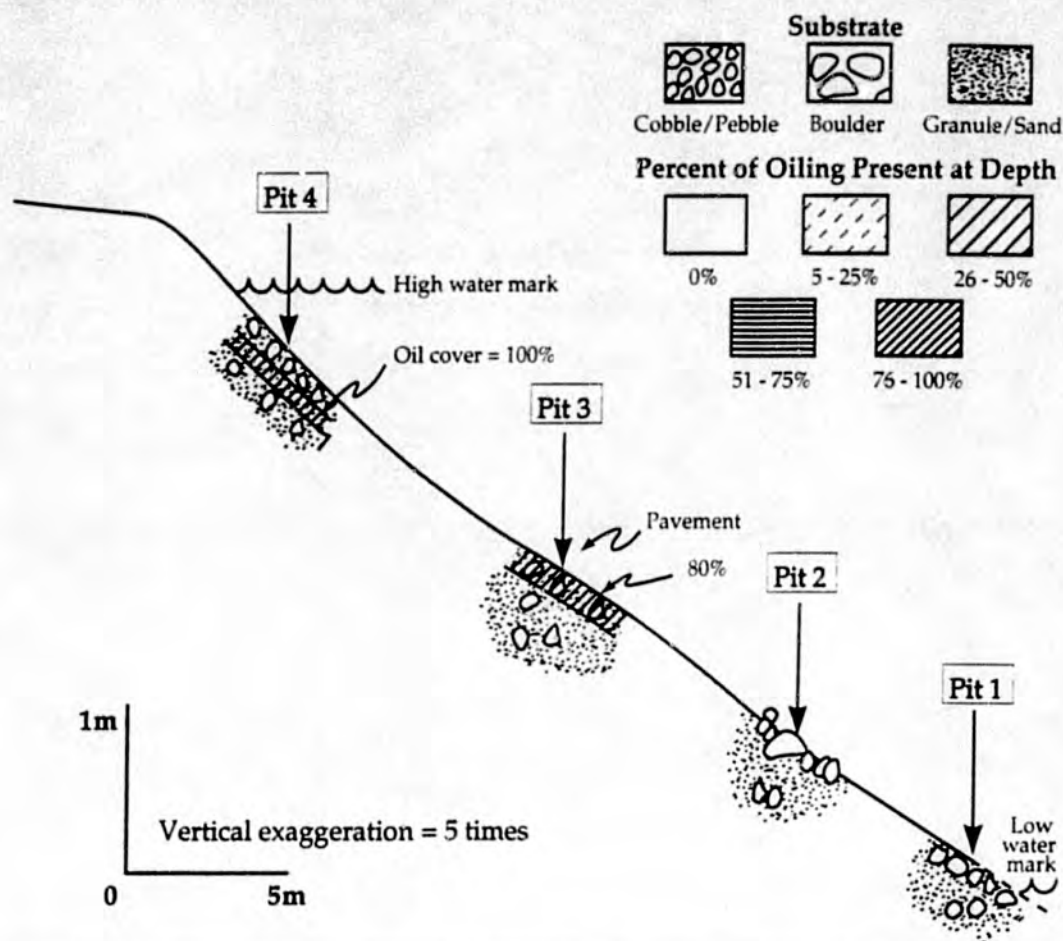
Over the winter and spring of 1990, more than 5,000 pits were dug (including SSAT and FASST surveys) to ascertain the character and penetration of subsurface oil. Oil that was observed in subsurface sediments had either penetrated down through pore spaces between the particles after stranding, or had been reworked or buried as a result of wave action redistributing beach sediments.

The many subsurface observations indicate that deep (50-100 cm) oil penetration was limited to a relatively few well-sorted, coarse-sediment beaches. Oil penetrated up to 1 m on a few coarse-grained beaches where no fine-grained sediments filled the large pore spaces between particles. This beach type is not common in the study area. Elsewhere, oil penetration was generally limited to the upper 10 cm of the beaches because fine-grained sediments have a low permeability to oil (Little et al. 1981; Michel et al. 1990). In addition, low permeability sediments retain more water on an ebbing tide, thereby further inhibiting penetration.

Most of the subsurface oiling information was collected during the spring 1990 SSAT survey. During that survey, oil was found at depths greater than 30 cm in 127 pits, along approximately 16 km out of the more than 2,000 km of shoreline that were surveyed. Two-thirds of this affected shoreline was accounted for in three stretches characterized by coarse-

Figure 8
Subsurface Pit Sketch/West Herring Bay

A cross-section of the beach at West Herring Bay shows that the presence of fine-grained sediments limited oil penetration. The oil found in Pit 4 on Jan. 18, 1990 was an asphaltic layer that had been covered by clean sediments.



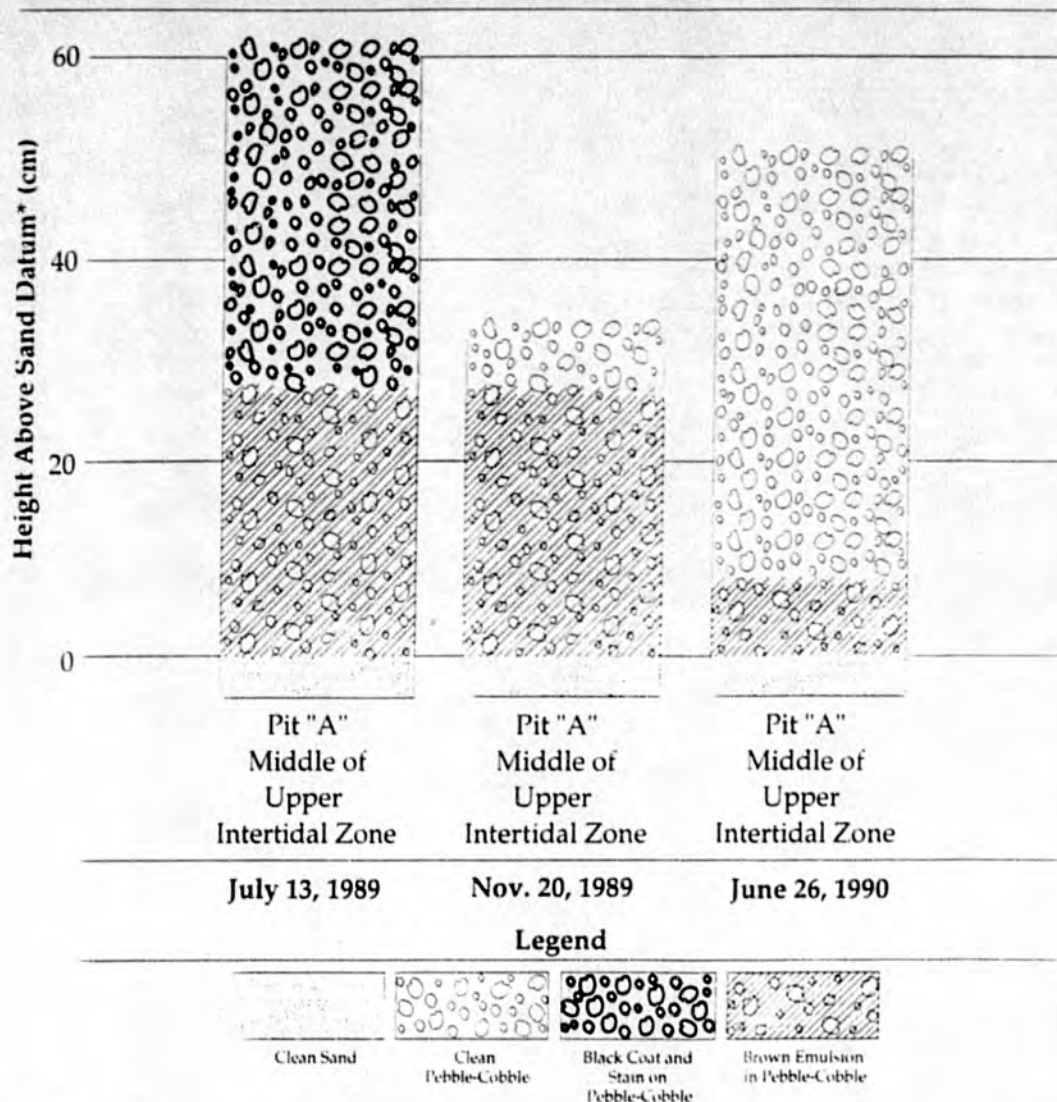
sediment beaches. Shorefast booms were deployed in April 1990 adjacent to these three beaches, which are long-term monitoring study sites (northeast Smith Island, AP-1; south Point Helen, AP-10; and Sleepy Bay, AP-13), to contain any oil that might be released as warmer summer temperatures reduced the oil viscosity. During site visits in the first week of June 1990, no oil was observed either contained within or stained on the booms, and during numerous overflights of these beaches no sheens were observed. The small quantities of oil that remained in the subsurface of these beaches in June 1990, therefore, appeared to be stable and not easily remobilized, which is consistent with other studies (NOAA 1990).

In general, oil was observed at greater depths on coarse-grained sediment (pebble-cobble-boulder) beaches than at locations where finer-grained sediments (sands and granules) were present. At the latter sites, the smaller interstitial pore spaces and the viscosity of the oil generally combined to limit penetration to depths on the order of 10 cm. An example of this condition is the upper intertidal zone of a sheltered beach in Herring Bay. Oil observed in Pit 3 at the site had penetrated to 12 cm (Figure 8, above). The limit of penetration coincided with a sediment change from mixed sand-pebble-cobble material to the same mixture plus gray mud. Field and laboratory studies have demonstrated that heavy crude oil does not

Figure 9

Subsurface Oil Changes Over Time/Sleepy Bay, Site AP-13

Pits dug on three different occasions at the same location at Sleepy Bay reveal changes in both beach surface elevations and subsurface oiling. The common datum for these pits is a fine grained, clean sand layer that limited oil penetration. Fall to winter 1989 wave action removed, reworked, and washed the pebble-cobble sediment cover, resulting in a reduced subsurface oiled layer (Photographs B-17 and B-18, on page B-6).



The datum used is the former seabed surface consisting of clean, well-sorted sand.

penetrate more than 1-2 cm where mud is present (Harper and Humphrey 1986). Pit 4 from the upper intertidal zone at the Herring Bay site provides an example of subsurface oil that resulted from burial of an asphaltic layer by a 10-centimeter-thick cover of clean sediment. TEH values from samples collected at the 20-25 cm depth layer in Pit 4 and from the top 10 cm in Pit 3 produced values of 1.4 and 2.4 percent oil-in-sediment by weight, respectively. Surface samples of TEH from Pits 2 (middle intertidal zone) and 4 produced values of 0.16 and 0.1 percent, respectively.

Results of reworking of subsurface oil were observed at Sleepy Bay (Figure 9, above; Photographs B-11 through B-18, on pages B-4 to B-6) where oil had penetrated the pebble-cobble upper intertidal zone to a depth of 60 cm (July 13, 1989). At 60 cm, the oil was prevented from penetrating farther by a zone of well-sorted sand (Photograph B-17, on page B-6; Figure 9, above). The sand appears to be the former nearshore seabed that was uplifted during the 1964 earthquake. A pit dug at the same location on Nov. 20, 1989 showed that:

- The top 25 cm of sediment had been eroded from the beach.
- The top 10 cm of the remaining oiled sediments had been reworked and cleaned.
- The zone of heaviest oil was a 25 cm thick layer.

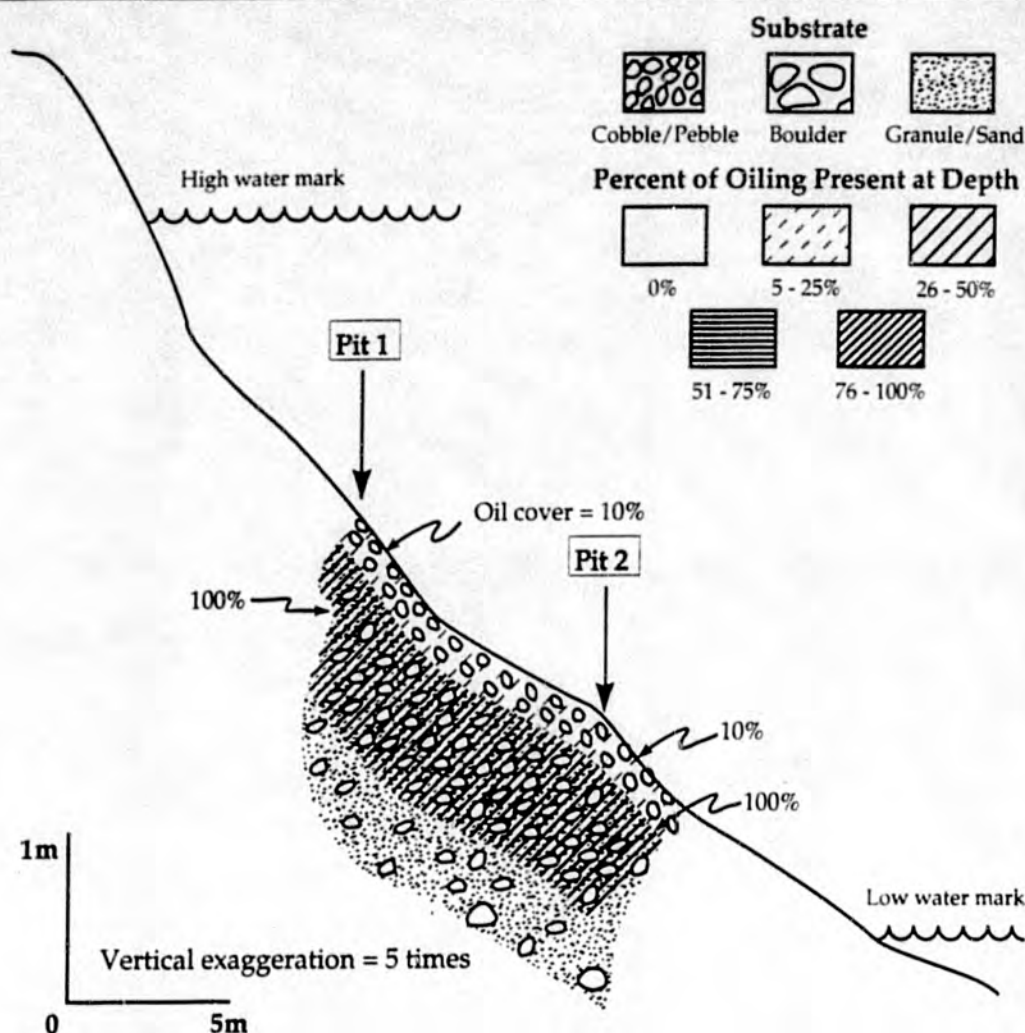
A pit dug on June 26, 1990 at the same location in the upper intertidal zone showed that the beach had been built up by constructive wave action almost to the same levels of the previous summer and that the oiled sediment zone above the clean sand was reduced to 10 cm in thickness (Photograph B-18, on page B-6; and Figure 9). Subsequent treatment activities, including tilling and bioremediation, addressed this oil lens.

Wave reworking also played a key role at study beach AP-1 on northeast Smith Island. This site was directly in the path of slicks from Bligh Reef, 35 km away. In April 1989, oil was observed to depths of at least 1 m. Surface washing during the summer of 1989 cleanup removed most of the surface and near-surface mobile oil, but deeper oil remained in September 1989. Storm wave action reworked sections of this beach to bedrock. This mechanical work exposed, washed, and abraded oil on the sediments such that no subsurface oil was observed in the intertidal sediments in trenches that were dug during a site visit on Nov. 20, 1989 in the central area of the beach near Transect 8, which is located on Figure D-1, on page D-4.

On some gravel beaches, sorting by wave action has produced a surface layer of coarse sediments, referred to as an armor layer, which overlies mixed fine and coarse gravel sediments. Armoring is very common on gravel coasts. Similar oil conditions with residues in the spaces between large surface sediments were observed at the "Arrow," "Metula," and "Nestucca" spill sites. The armor layer is often composed of uniform-size cobbles, such as at south Point Helen (AP-10). At this site, oil washed ashore, filled the large void spaces between the surface cobbles, and became pooled on top of the finer gravel sediments beneath the armor. This oil was then sheltered from wave washing and, with time, penetrated through the gravel to depths of several tens of centimeters. This subsurface oil was protected by the armor layer from wave action over the 1989-90 winter. Two pits dug in the upper intertidal zone at the south Point Helen site AP-10 in January 1990 showed oil to depths of 95 and 100 cm, below which no oil was present (Figure 10, on the next page). Prior to Jan. 19, 1990, oil had been removed from the surface armor layer of sediments on this beach by high energy waves during winter storms. Physical abrasion had cleaned the surface armor layer, but the depth of reworking and abrasion extended only to depths of 25-30 cm. TEH values from the 40 and 80 cm levels in Pit 2 produced values of 0.15 and 0.09 percent, respectively.

Figure 10
Subsurface Pit Sketch/South Point Helen, Site AP-10

A cross-section of the beach at Point Helen shows oil in sediments to a depth of 1 m in January 1990. Pooled oil was trapped between the cobbles of the surface armor layer and penetrated the gravel, where it remained protected from wave action.



Changes in Sediment TEH Data

Experience has shown that oil-in-sediment data from coarse-sediment (pebble-cobble) beaches do not conform to a normal distribution. Therefore, the monitoring program was designed to collect sediment samples for analysis only to provide general information on trends in the oiling conditions at the study sites. Data presented in this report and elsewhere (Jahns et al. 1991) indicate that oil-in-sediment concentrations have decreased with time at most sites, in both surface and subsurface data sets. This trend is consistent with other data collected by the monitoring program (i.e., surface oil cover, subsurface oil conditions) and with observations made during other survey programs.

More than 1,000 beach sediment samples from the study sites were collected and analyzed for hydrocarbon content. The sampling followed a systematic plan in which the same zones were sampled along the same transects on most occasions. The results provide a general indication of changes in oil-in-sediment concentrations through time. Two major features of the data set are particularly noteworthy:

Data from 12 sites show a general reduction of average TEH values.

Table 9
Summary of Average Surface Oil-in-Sediment from the Upper Intertidal Zone

Exposed Sites	Summer 1989 (mg/kg)	Fall 1989 (mg/kg)	Late Winter 1989-90 (mg/kg)	Summer 1990 (mg/kg)
AP-1	1,500	600	30	1,600
AP-8	3,600	700	900	N/A
AP-10	2,900	2,200	1,500	500
AP-12	2,800	1,100	1,200	300
Moderately Exposed Sites				
AP-5	2,700	N/A	50	250
AP-14	1,700	2,500	500	350
AP-15	2,500	N/A	350	1,000
AP-16	1,100	1,400	600	6,500
AP-17	850	2,700	20	150
Sheltered Sites				
AP-4	5,700	4,700	50	150
AP-6	N/A	8,400	10,000	4,000
AP-18	2,800	900	2,800	3,500

Note: Values expressed as percent in text. Example 600 mg/kg = 0.06%
N/A: Not available

- The samples were collected from study sites where the initial oil concentrations were high.
- Data from beaches composed of mixed coarse sediments are quite variable so only major trends are indicative of genuine change (Humphrey et al. 1990).

The data from the Kenai-Kodiak region are not reviewed in this report because the oil deposits outside of the Sound were very scattered and patchy, which means that individual data points are site specific and may not represent general trends.

In the Sound, the lower one-third of the intertidal zone was not heavily oiled initially. The 30 surface samples collected from this zone at different sites between May and August 1989 have an average value of 0.05 weight percent (equal to 500 milligrams (mg)/kilograms (kg); 1 percent = 10,000 mg/kg), whereas the mean for 78 samples from the middle and upper intertidal zone over the same time period is 0.17 percent. Average values do not reflect the wide range in the data set that is typical for this type of study; however, the analytical results for the Sound show reductions of oil concentrations over the winter period. Table 9, above, lists average TEH

values from surface samples collected in the upper intertidal zone, where oiling conditions were initially heaviest. This table includes only sites where a long-term data set is available.

The TEH values from three of the four exposed sites show decreasing concentrations over time. The values at six of the 12 sites – in particular, AP-12 (exposed), AP-5 (moderately exposed), and AP-4 (sheltered/moderate) – were clearly reduced, and the average of all upper intertidal zone samples from these 12 sites dropped from 0.26 to 0.15 percent between fall 1989 and late winter 1990. Similar trends are evident from the larger data set described by Jahns et al. (1991), which shows a decrease in the average from 0.36 percent to 0.16 percent over the 1989-90 winter months.

No subsurface samples were collected before September 1989. The results from the winter sample collection program show average subsurface TEH values of 0.35 percent for September 1989 and 0.10 percent for March 1990. This change indicates that winter wave action was able to rework, wash, and abrade the subsurface sediments on the study beaches. Additional reduction in oil quantities resulted from tidal pumping and biodegradation.

DISCUSSION

Most of the oil initially stranded on the Prince William Sound and Kenai-Kodiak shorelines was gone as of the September 1990 surveys, though remnants of oil remained, often as small patches in sheltered locations or as stains and coats on the sediments. All of the trends from the monitoring program show that the shorelines had recovered as a result of cleanup operations and natural cleaning. The lighter hydrocarbons, which are the most mobile and toxic components of crude oil, were removed by natural weathering, so the remaining oil cover was a stable and often tar-like substance. Subsurface oil was still present at only a few sites in the Sound as of September 1990.

The 1989 cleanup program focused on washing and collecting mobile oil from the shoreline. The success of this program is evident from the field observations on heavily oiled study beaches that were washed extensively. By September 1989, there was a significant decrease in surface oil cover at these sites. This change in surface oil cover understates the overall reduction in oil on the shoreline because it does not take into account the removal of mobile oil that was washed from the beaches. The general absence of asphalt pavements, which typically form on heavily oiled gravel beaches, is additional evidence of the effectiveness of the 1989 washing program.

Rates of natural cleaning varied, depending on the particular shoreline character and oil conditions at each site. The level of effort in the 1989 treatment program was also a factor in the changing oil cover. At AP-1, which was treated twice by large work crews over several weeks because of the sensitivity of nearby seal haulouts, the oil cover was reduced to 28 percent by September 1989. Similarly, a high level of effort at the Applegate Rocks haulout site removed virtually all of the surface and subsurface oil by May 15, 1989. At sites that were not extensively washed during 1989 (AP sites 2, 10, 11, 12, 13W, and 15) surface oil cover in August/September 1989 ranged between 37 and 63 percent, with a mean of 48. This indicates that the higher level of treatment effort contributed to cleaning the surface sediments.

In 1990 the focus of the treatment activities shifted to the oil residues. Most of the oil observed after the 1989-90 winter remained because it was out of reach of wave action or treatment activities. Oil residues were found beneath crevices, above the limit of normal wave action, and, at some sites, below the surface sediments. Manual removal, sediment (berm) relocation, and bioremediation were the primary techniques used in 1990 to pick up weathered oil, expose oiled sediments to wave action, and promote biodegradation, respectively. These programs were effective in further reducing the amount of remaining oil. Sediment removal was avoided because there is a paucity of material on the beaches of the Sound and little or no contemporary source of coarse sediments to the coastal zone. Experience with sediment removal following the "Arrow" spill, in a similar coastal environment, shows that removal of coarse material in this type of situation leads to beach erosion.

Subsurface oil was limited in extent because large portions of the coast are either bedrock outcrops or gravel (mixed sediment) beaches where penetration is restricted by the nature of the substrate. In particular, little subsurface oil was observed in sheltered environments because these beaches typically have a high proportion of fine-grained sediments. Burial of oil by sediment redistribution was observed at only a few locations. Burial of oil residues was not considered a systematic problem because this region had little influx of new sediment to the coastal zone and, therefore, few locations of sediment buildup. The few locations where subsurface oil remained after the summer of 1990 generally were sites where oil was able to penetrate into well-sorted pebbles and cobbles on exposed beaches. Also, at some locations with a surface layer of well-sorted coarse material, oil was concentrated between the sediments and protected from summer wave action by the surface armor layer. This oil was able to seep into the subsurface material and some of this oil remained there protected by the surface (armor) layer from subsequent winter wave action.

The trends observed at the study sites were confirmed by ground, boat, and helicopter inspections of other sections of coast over the study period. The surface oil-cover changes are well illustrated in the transect maps. The oiling trends depicted in the maps, and quantified in the tables and graphs, probably underestimate changes that took place over 18 months. The study sites selected, for the most part, were beaches with an initially heavy concentration and a wide band of oil. These beaches were the most difficult and slowest to clean, either by man or nature.

A reconnaissance of the Northwest Bay and Upper Passage coastline during the second week of January 1990 marked a distinctive turning point in documenting natural cleaning in these sheltered environments because, for the first time, extensive sections of the previously oiled intertidal zone were noticeably oil-free. These shorelines had been washed and most of the mobile oil removed throughout the summer of 1989, leaving a coat or stain on bedrock and sediments. The area had not been visited for six weeks before January 1990, and the changes in surface oiling were obvious and widespread. The natural cleaning of oil residues from these sheltered, low wave-energy environments occurred much more rapidly than expected. Laboratory studies point to the role of physico-chemical weathering as a significant factor in the natural removal of this residual oil (Jahns et al. 1991). This natural cleaning process probably would not have been effective with heavy concentrations of residual oil.

The observed changes in surface oil cover document the initial changes that were due to the 1989 treatment program. During the winter of 1989-90 wave action was the primary process by which exposed shorelines were cleaned. At the same time, natural removal of oil was taking place in sheltered environments due to biodegradation and to the interaction of the suspended sediments and seawater with the surface of the oil to form solid-stabilized emulsions (Bragg et al. 1990). These bio-physical weathering processes were more important in sheltered environments due to the diminished role of wave action.

Beach elevation transects illustrate the effects of winter storm wave action on exposed, and some relatively sheltered, sites. Winter erosion combed down, reworked, abraded, and washed the sediments to depths of more than 1 m at some sites, and constructive spring and summer wave action subsequently returned clean sediments to the beaches. The winter months from January 1990 onward were relatively free of severe storms, as is common in this region. Hence, overall levels of late winter and spring wave energy at the shoreline were lower than in the early winter (September to December 1989).

Detailed analysis of the transect data shows clearly that oiling was initially less extensive in the lower one-third of the intertidal zone, and that through time the remaining surface oil was concentrated on the uppermost sections of the shore. This is significant on most shoreline types, including gravel beaches, because the biological communities are richest in the lower intertidal areas.

Oil-in-sediment (TEH) data do not always exactly reflect observed changes at most sites. This discrepancy has been recognized in previous studies and is a result of the difficulty in sampling coarse-grained sediments. Oil concentration data have been found to be extremely variable in mixed and coarse-grained sediment environments. This type of data best represents oiling conditions for sand beaches (Humphrey et al. 1990). Two trends, however, can be deciphered from the Sound data: (1) The lower intertidal zone did not initially, or subsequently, have high oil-in-sediment concentrations; and (2) there was a general reduction of oil-in-sediment concentrations over the 1989-90 winter months (Jahns et al. 1991).

The intertidal ecology program used photographic surveys of key surface organisms on 44 oiled sites where 183 transects in total were sampled. Sites that were surveyed in September of 1989 and 1990 were compared to assess the rate of biological recovery during the year. These sites were then compared to unoiled reference sites surveyed in September 1990 to evaluate the extent of recovery. The comparisons reveal that the distributions and abundances of key organisms on most oiled sites by September 1990 were not substantially different from those on the unoiled reference sites. Lower rates of biological recovery appear to have occurred on some heavily oiled sites that were not extensively treated to remove bulk oil in 1989.

The data from the monitoring sites clearly demonstrate the reductions in the surface oil cover over the 18-month study period. The fact that significant reductions occurred over the 1989-90 winter on both exposed and sheltered sites indicates that other processes, in addition to wave action, can be important in the natural cleaning of the oiled shorelines. Greatest emphasis is given to the oil cover data; nevertheless, general trends are evident in other data sets, including the reduction of subsurface oil and the natural recovery of key intertidal species.

CONCLUSIONS

Program

- The study sites focused on beaches that were initially heavily oiled, thus biasing the study toward worst-case conditions. Therefore, the amount of oiling discussed in this report is not representative of shoreline conditions throughout the region. However, one would expect to find less oil on most other shorelines.
- The monitoring program required a considerable commitment, but as a result, this is the best-documented and most-studied spill to date.

General Observations

- Significant reductions of oil conditions have been documented.
- The 1989 treatment program accelerated the rate of recovery, so most shorelines were free of oil after 18 months.

Oil Cover

- The combined oil cover for the Sound study sites dropped from 46 percent of the total observed area in May 1989 (six sites only) to 39 percent in August 1989, to 12 percent by January 1990, and to less than 2 percent by September 1990.
- The original oiled area on two of the exposed Kenai-Kodiak sites with wide-band oil was reduced to 7 percent at AK-4 by January 1991 and to less than 1 percent at AK-5 by March 1990.
- Analysis of transect data showed that oil cover changes were related to treatment activities and to wave action. For example:
 - The first treatment phase at the northeast Smith Island site (AP-1) reduced the oil cover from 100 percent to 79 percent; the second treatment further reduced the cover to 44 percent and winter wave action reduced it to 1 percent.
 - At the moderately exposed AP-4 site in the Sound, most of the oil cover change (from 33 to 12 percent) occurred over a four-week period in mid-winter.
- Rates of natural cleaning varied from site to site, depending on site exposure and the coincidence of onshore storm-generated waves with the fetch window of a beach.
- The removal of mobile oil by the 1989 washing program enhanced biodegradation and physico-chemical weathering.

Subsurface Oil

- Subsurface oil was not common on the shorelines affected by the spill, and few beaches contained any oil within the subsurface sediments as of September 1990.
- Oil penetration was largely restricted to depths on the order of 10 cm because of the presence of relatively fine-grained subsurface sediments on the majority of beaches in the study region. Bedrock outcrops form the shoreline or underlie a coarse-sediment veneer on 70 percent of the oiled coasts of the Sound.
- At a few locations where beaches are composed of coarse sediments, the oil had penetrated as much as 1 m deep; these beaches are typically exposed, high wave-energy environments and, in some cases, were reworked to depths of 1 m during the winter (for example, at AP-1).
- By June 1990 the remaining subsurface oil appeared stable, releasing neither oil nor sheens to the nearshore waters (NOAA 1990).

Sediment TEH Data

- The results from oil-in-sediment studies on mixed or coarse-grained sediment beaches provide a highly variable data set.
- There is a trend of oil concentration reduction through time that is consistent with all other field observations and data sets.

Beach Changes

- Wave action caused sediment reworking and redistribution, with washing and abrasion of oiled sediments, on most beaches.
- Wave activity was greatest on exposed Kenai-Kodiak beaches, with documented erosion and deposition greater than 1 m at some sites.
- Similar erosion was recorded in parts of the Sound, with reworking down to 1 m at exposed study sites.
- Beaches rebuilt during the spring of 1990 at most locations as constructive waves returned sediments to the intertidal zone.
- Sediments were also reworked on sheltered and moderately exposed beaches.

Winter Winds and Waves

- The dominant and prevailing winds in the Sound were out of the eastern quadrant from September 1989 to June 1990.

- Approximately 18 storm events occurred during this time; six major storms occurred before January 1990, with peak winds in excess of 85 km/hr or a daily average wind speed greater than 40 km/hr.

Biological Observations

- Photographic monitoring of surface biota over a one-year period to September 1990 shows that at most oiled study sites the abundance and distribution of key intertidal species were not substantially different from those at non-oiled sites.
- Ecological recovery appeared to be enhanced at some sites where 1989 treatment activities (flush and flood) were able to remove the majority of the bulk oil.

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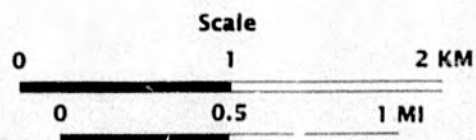
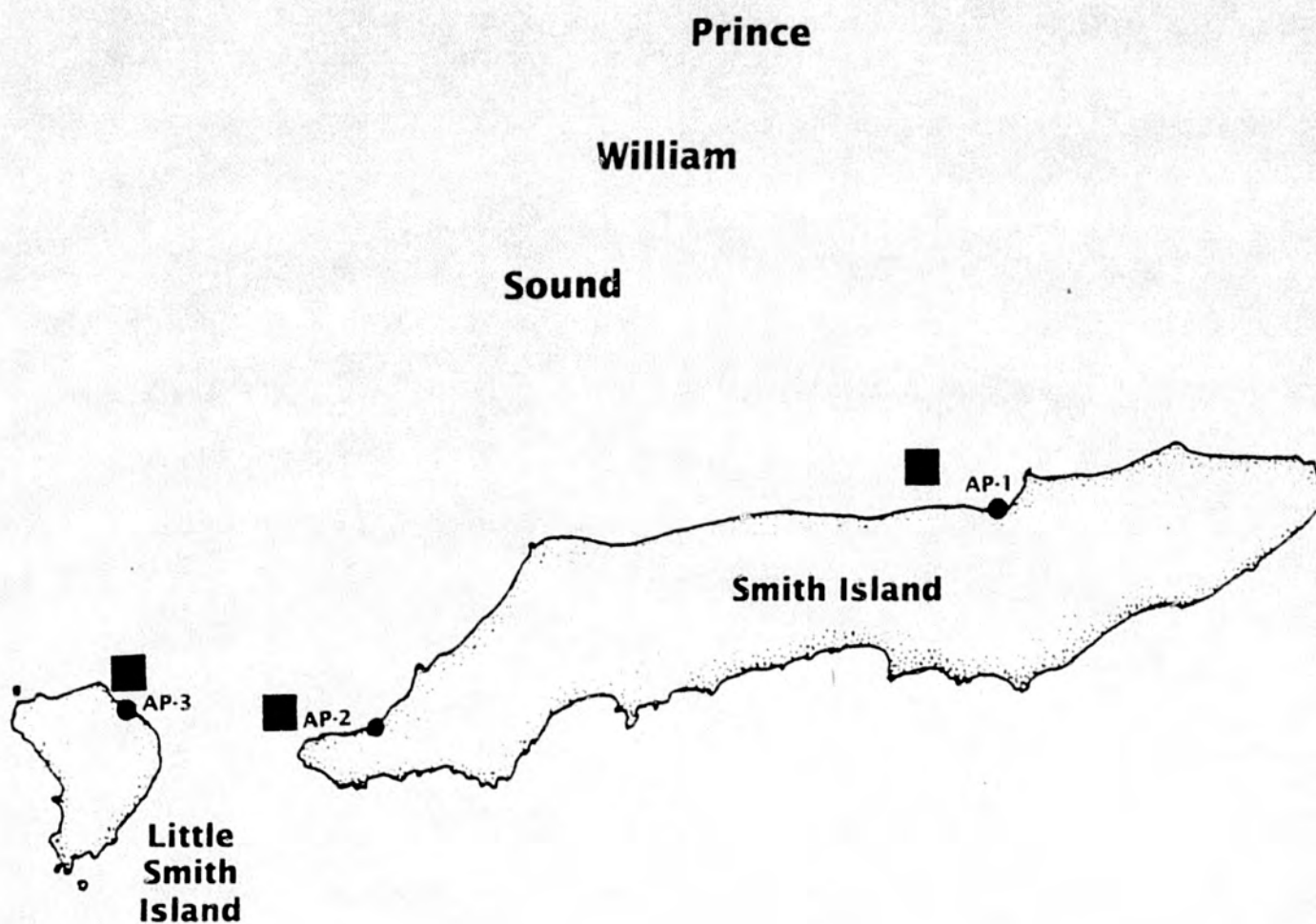
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APPENDIX A

Site Location Maps

Twenty-eight locations were surveyed beginning in the spring and summer of 1989 to document changes in oil cover through time. Figures A-1 through A-9, on the following pages, show the location of these sites on detailed maps. Overview maps are shown in Figures 2, 3, and 4, on pages 6, 7, and 8.

Figure A-1
Site Location Map/Smith Island



Wave-Energy Environment

-  Exposed = Unprotected shoreline and large fetch area
-  Moderate = Some unprotected shoreline and intermediate fetch area
-  Sheltered = Protected shoreline and/or short fetch area

Figure A-2
Site Location Map/Knight Island

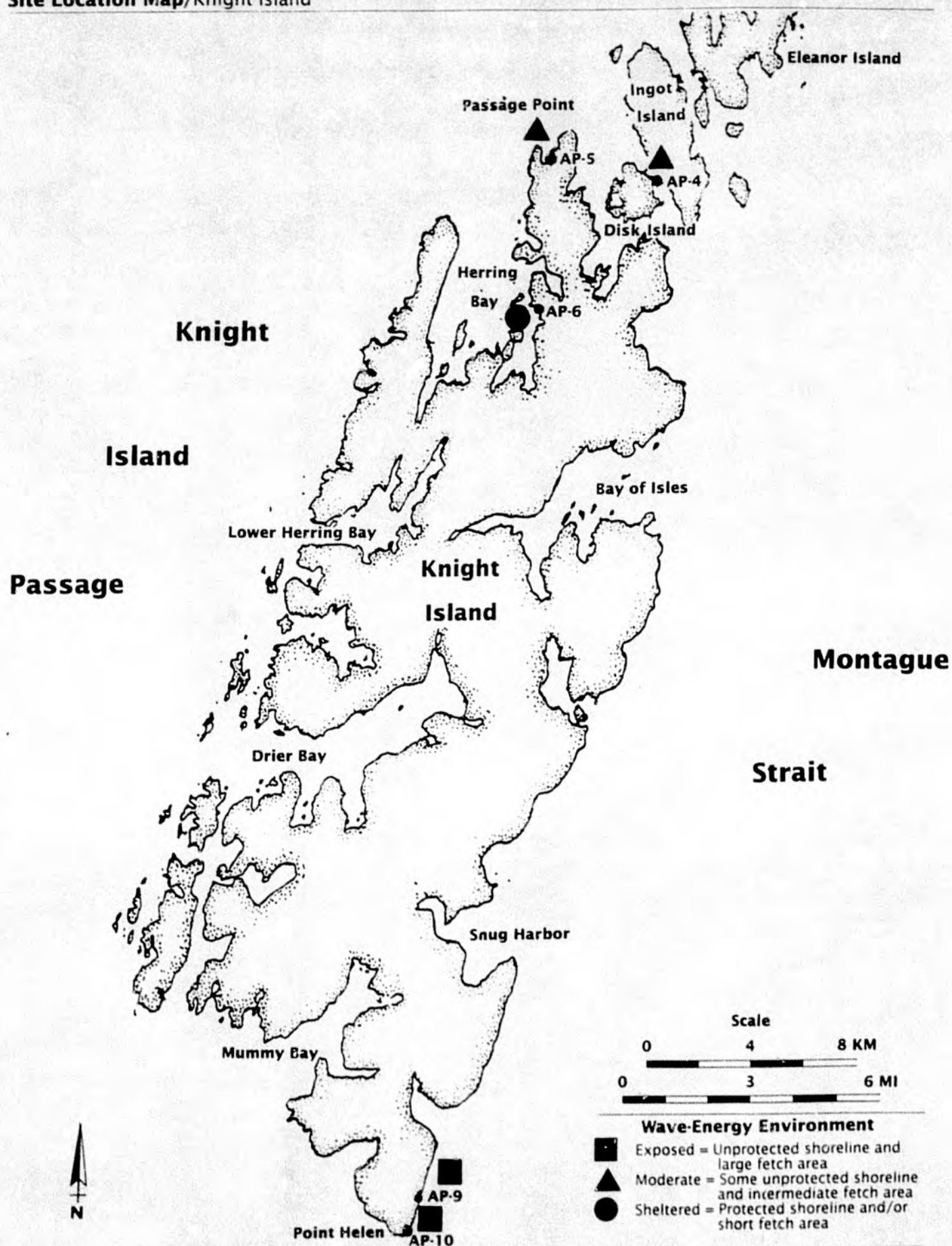


Figure A-3
Site Location Map/Green Island

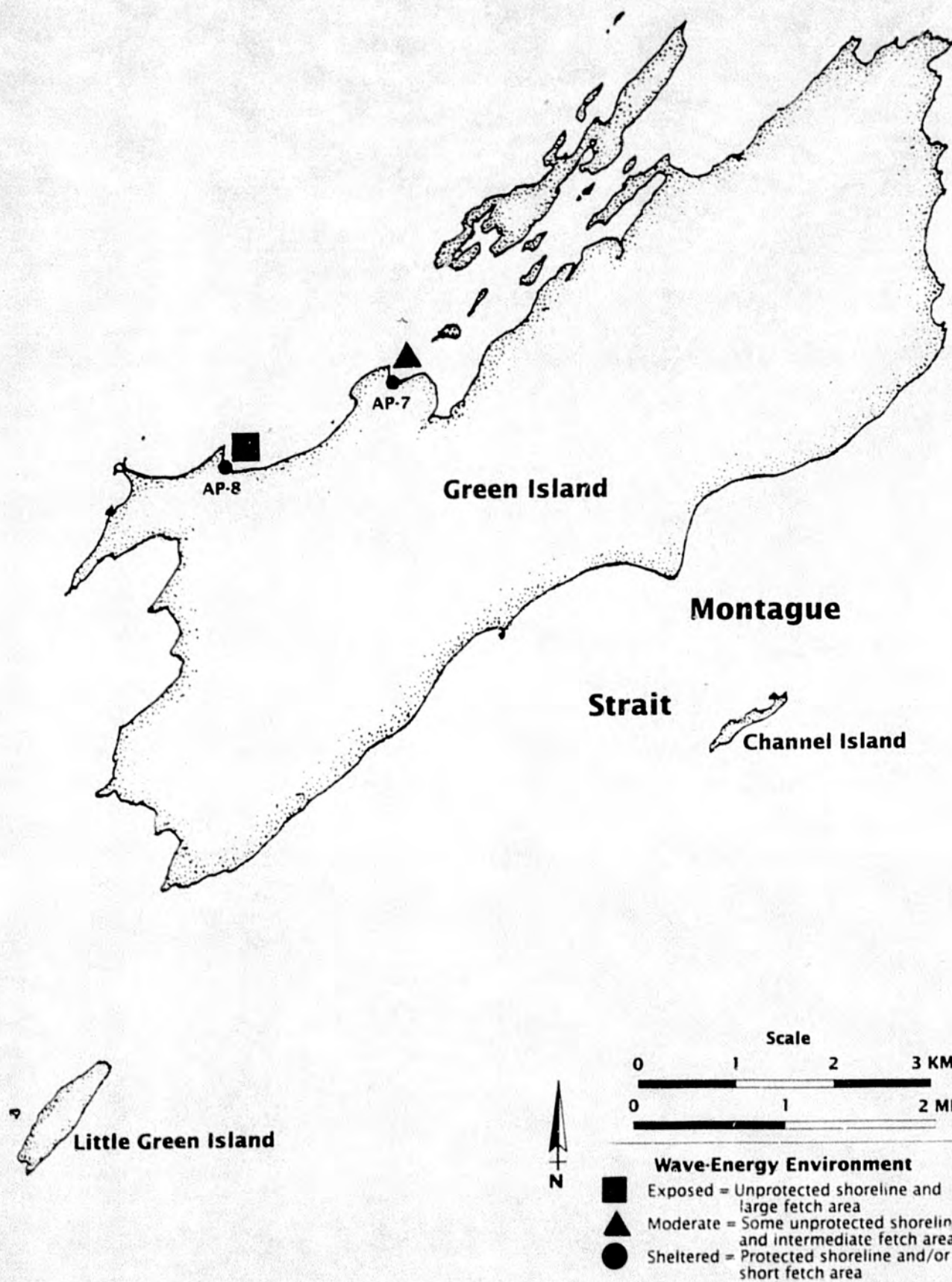


Figure A-4
Site Location Map/Latouche Island

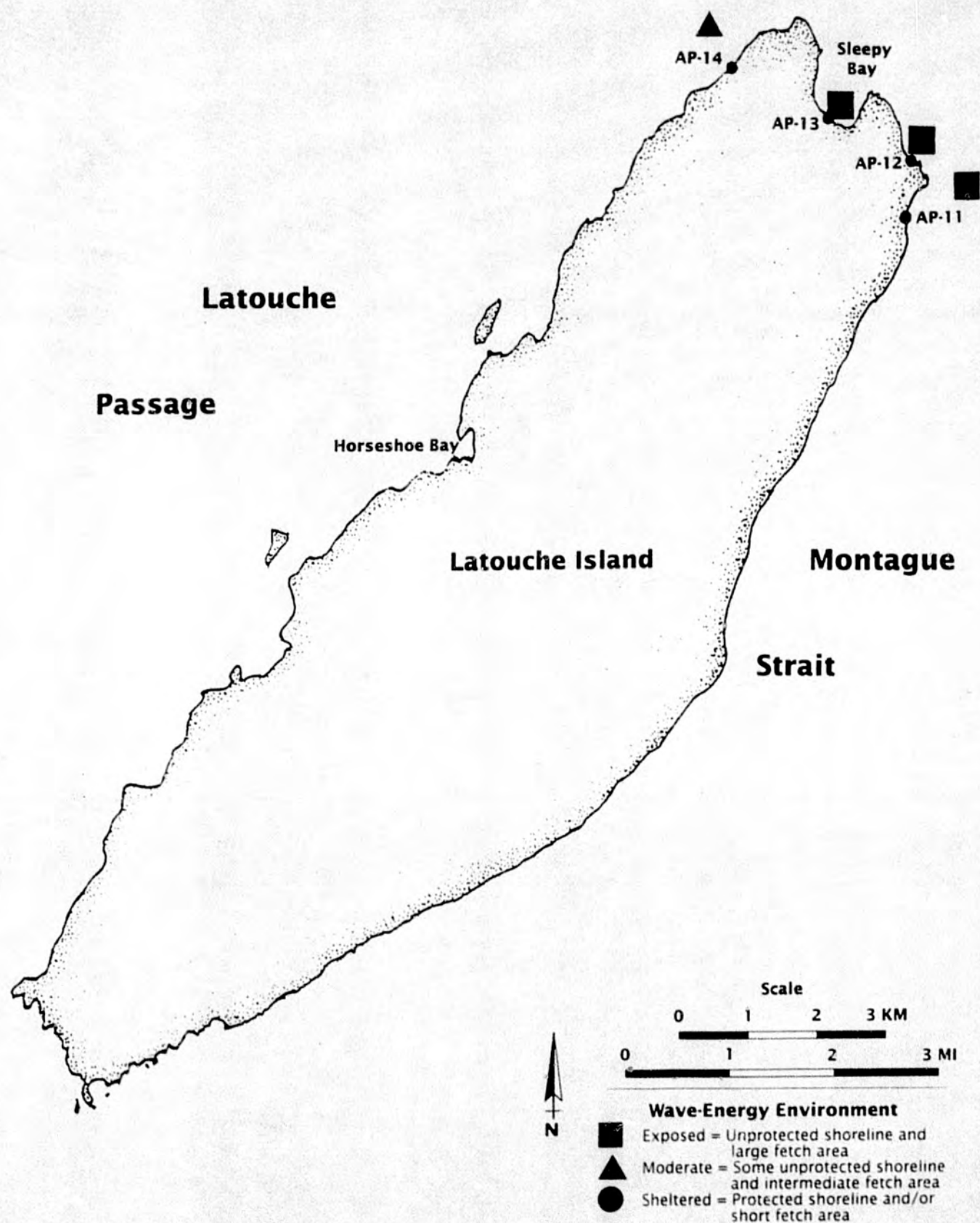


Figure A-5
Site Location Map/Evans Island

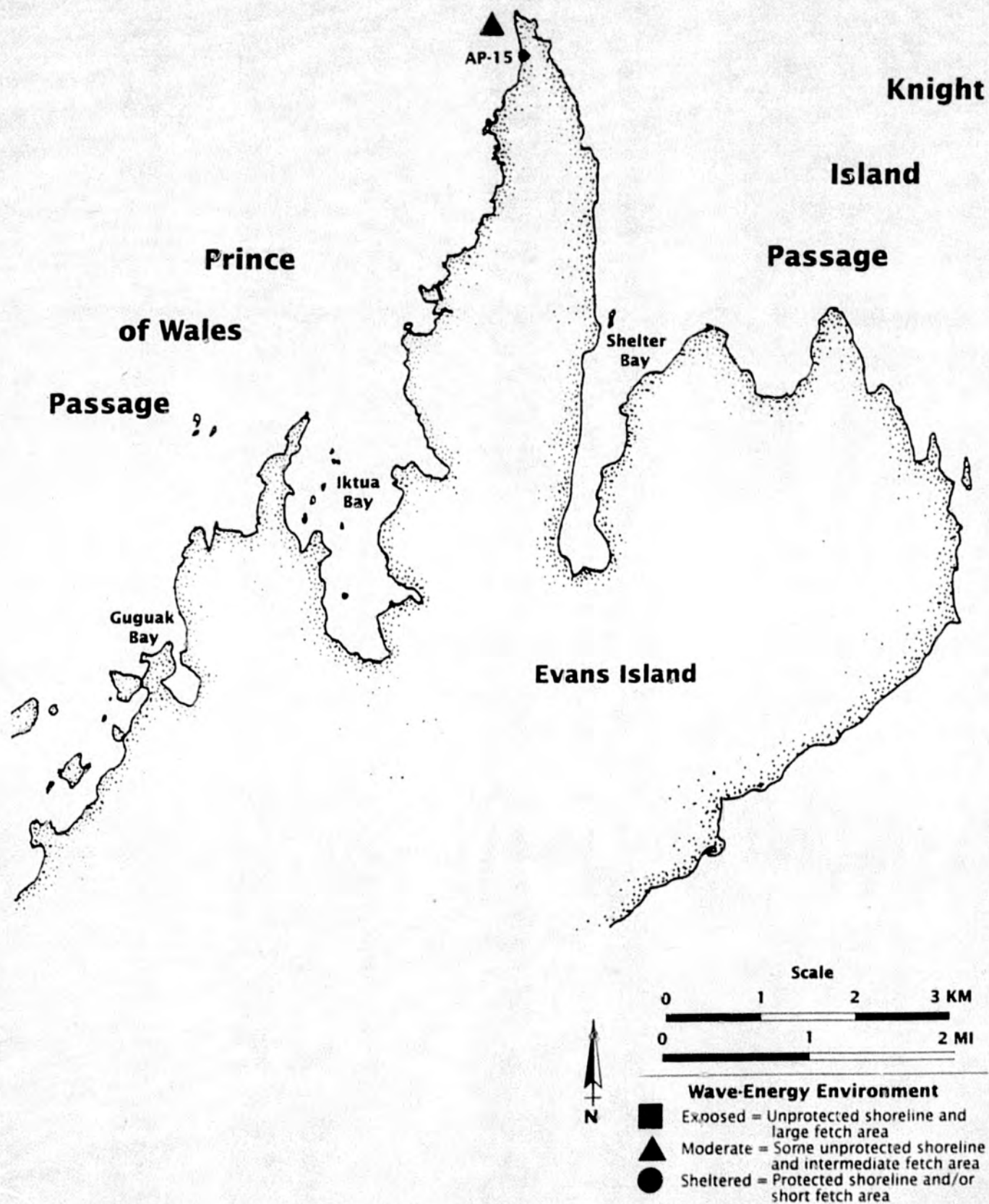
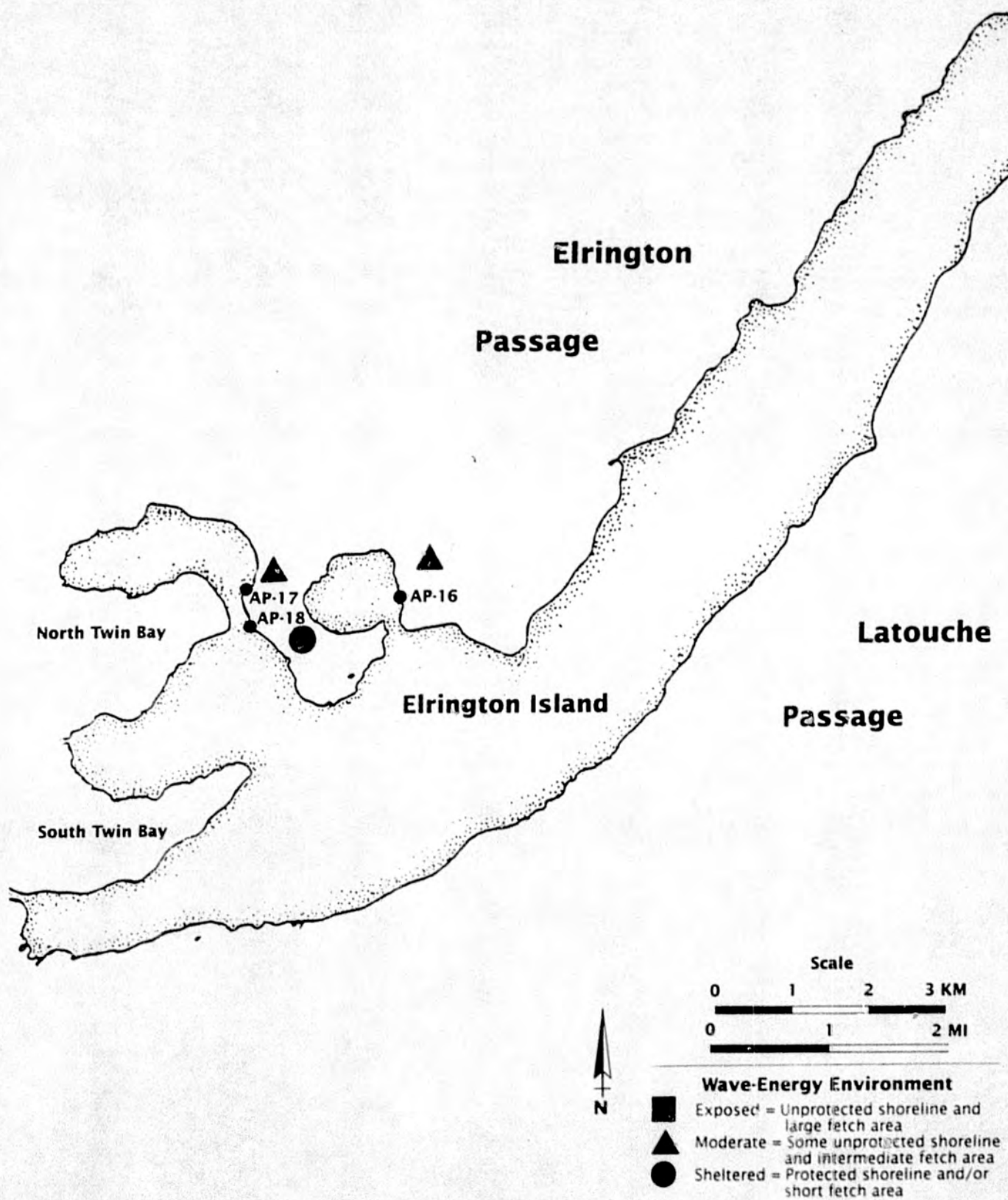


Figure A-6
Site Location Map/Elrington Island



8-V Figure A-7
Site Location Map/Kenai Peninsula

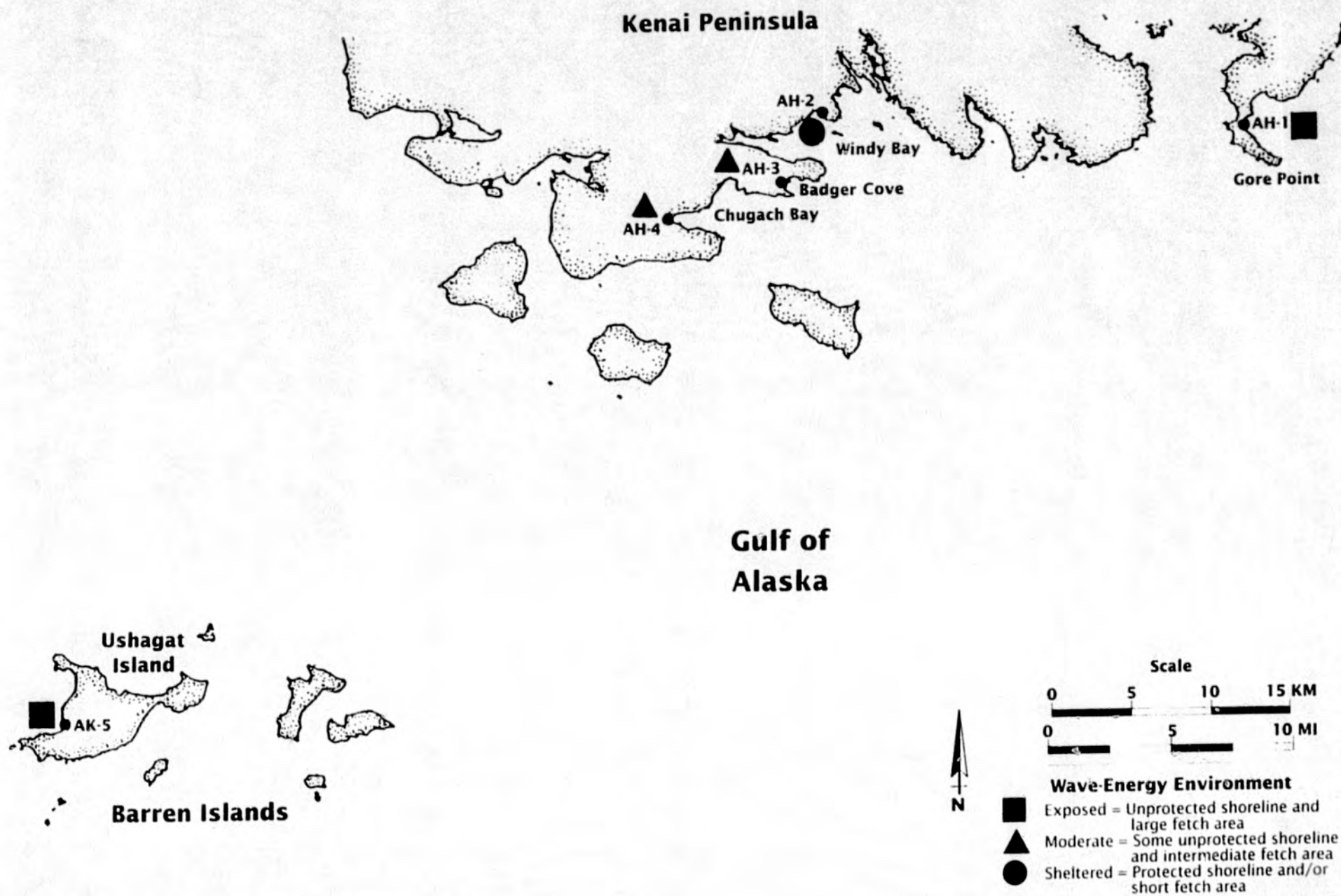


Figure A-8
Site Location Map/Afognak Island

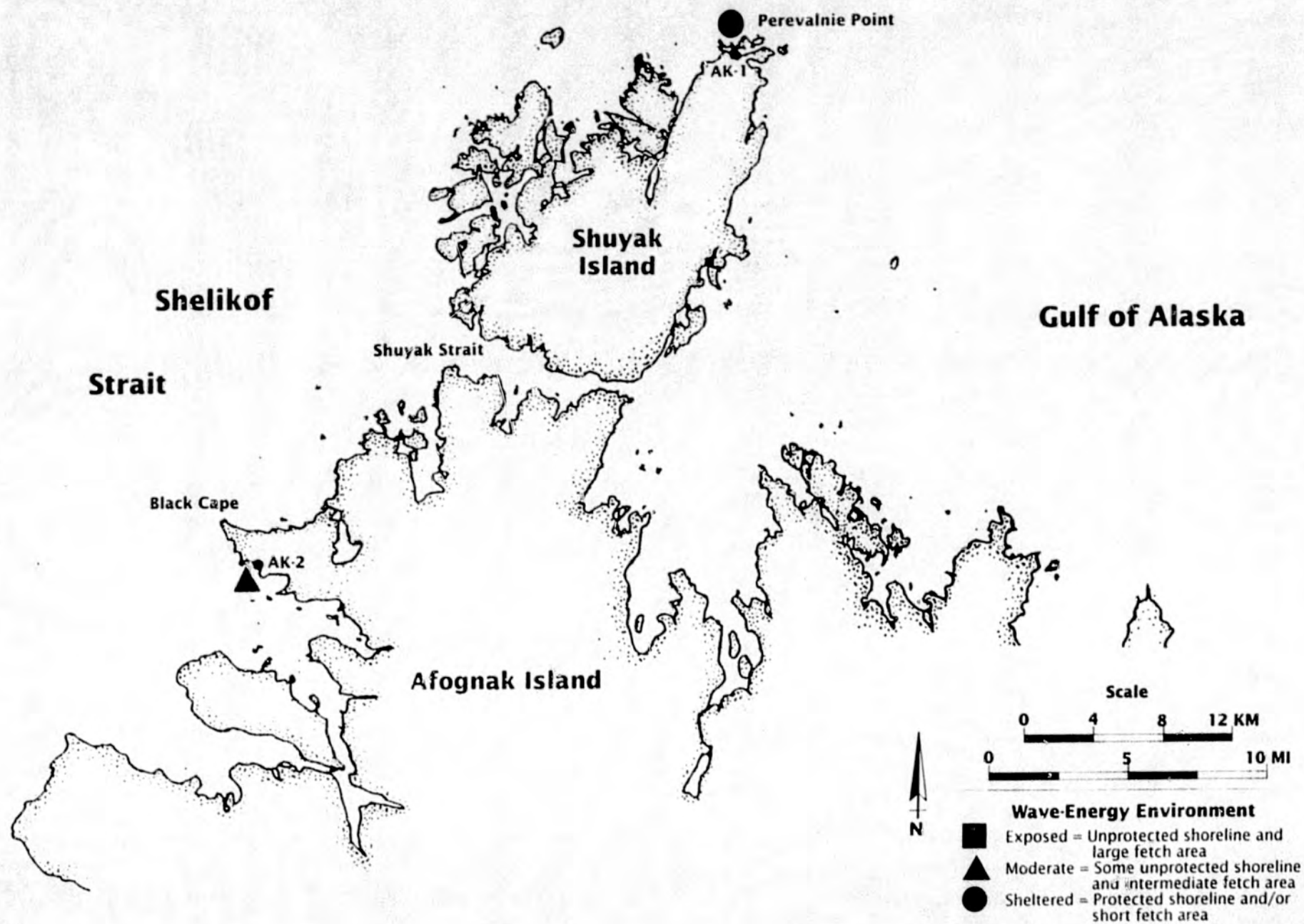
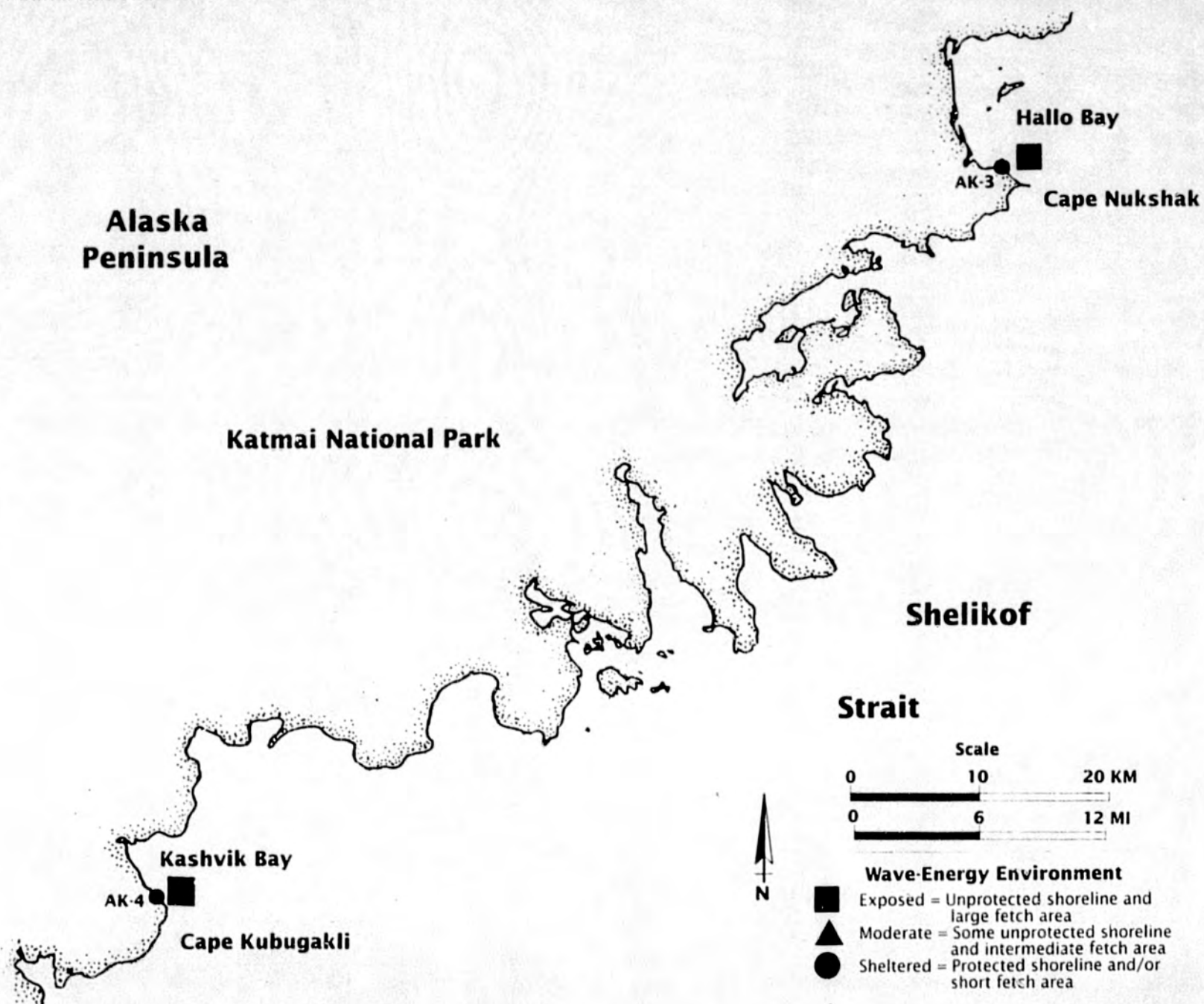
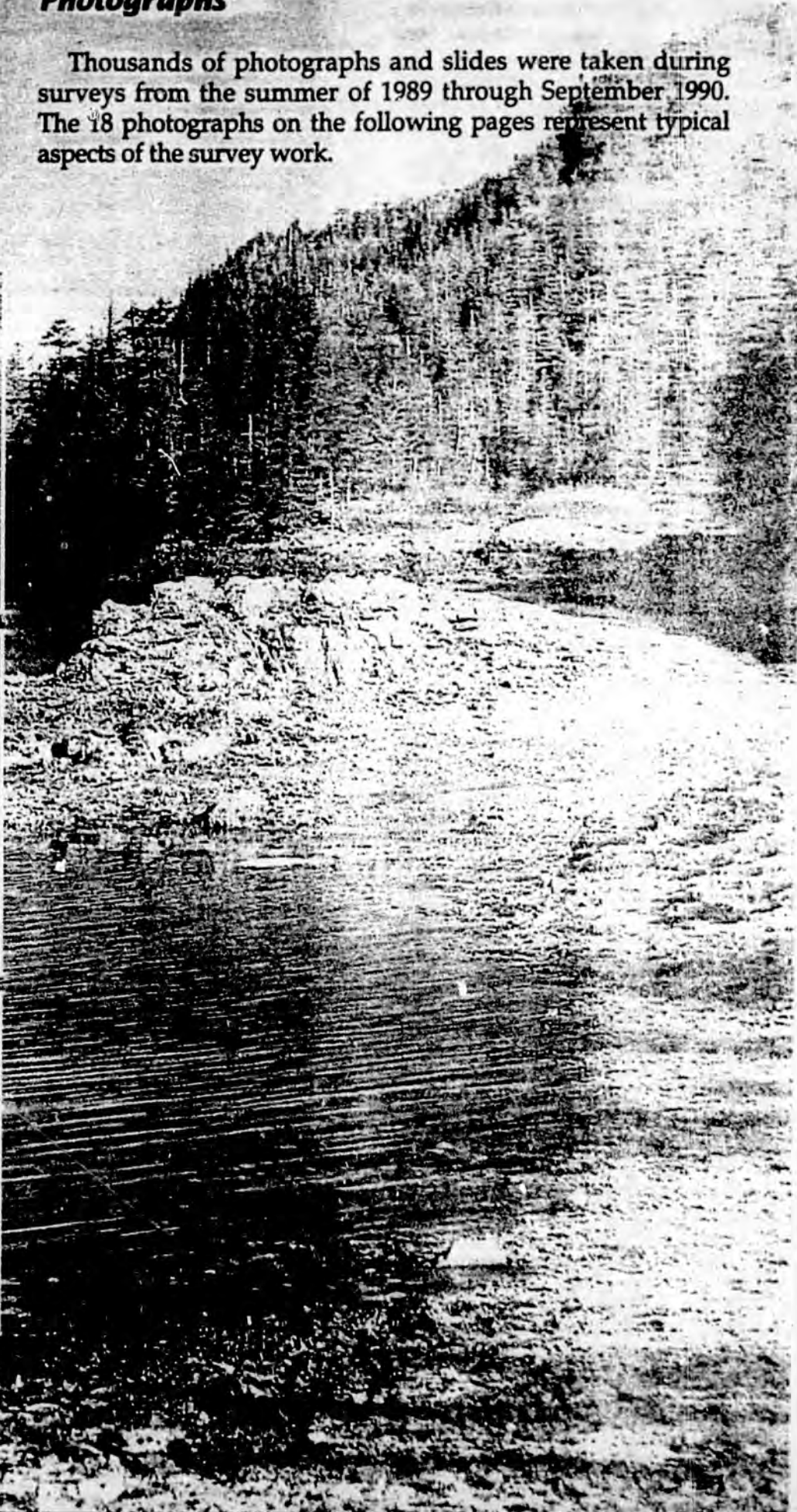
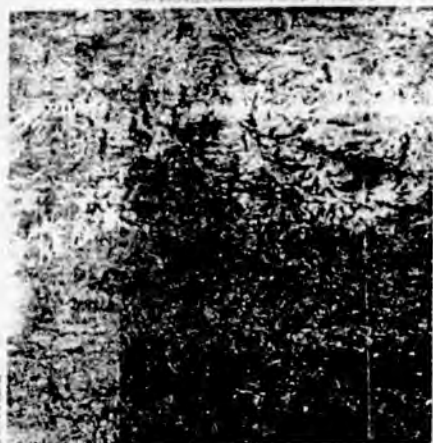


Figure A-9
Site Location Map/Katmai National Park



**APPENDIX B*****Photographs***

Thousands of photographs and slides were taken during surveys from the summer of 1989 through September 1990. The 18 photographs on the following pages represent typical aspects of the survey work.



Photograph B-1- This beach and rock headland on southern Lone Island typify many of the shorelines in the Sound. This June 1990 photograph shows dark bands of lichen (marked by a bracket to the right of the photograph) and patches of mussels (marked by an arrow), not oil, on the rocks. Such features are found widely throughout the Sound. This site was oiled in 1989 but clean by the time of this visit. ►



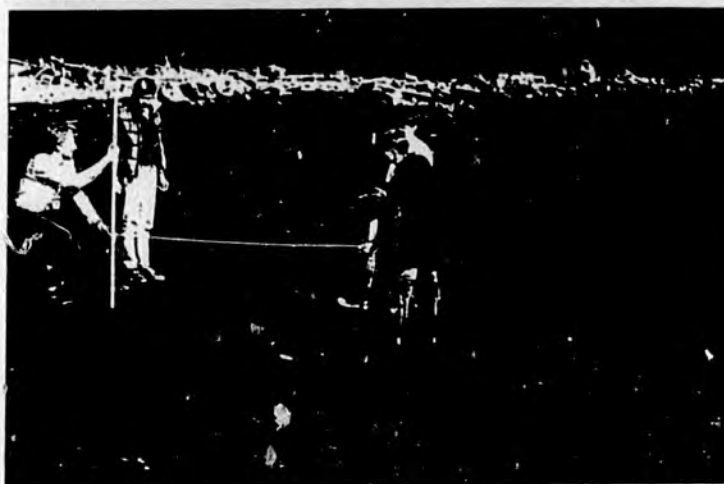
B-1

Photograph B-2- This general view shows a rugged, exposed, high wave-energy coastline on the Kenai Peninsula on a calm summer day. The photograph was taken at northeast Black Bay on June 27, 1989. ►



B-2

Photographs B-3 and B-4- Survey teams worked along transects oriented approximately perpendicular to the shoreline. Field activities included surface and subsurface oil cover observations, photographic and videotape records, sediment sampling, and beach elevation profiles. Beach elevations were usually surveyed using the Emery method by taking readings every 2 m along a transect (Photograph B-3, taken at Ingot Island, site AP-4, on Sept. 15, 1989). Pits were dug to examine the extent of subsurface oiling (Photograph B-4, taken at west Knight Island, March 17, 1990). ►



B-3



B-4

Photographs B-5 and B-6—
 These photographs show
 views to the west of the
 beach at site AP-1 on
 northeast Smith Island.
 Photograph B-5, taken on
 May 2, 1989, shows the
 initially heavily oiled beach.
 The same beach was
 virtually clean by June 12,
 1990 (Photograph B-6). The
 arrow indicates the location
 of closeup Photographs B-9
 and B-10.



B-5



B-6



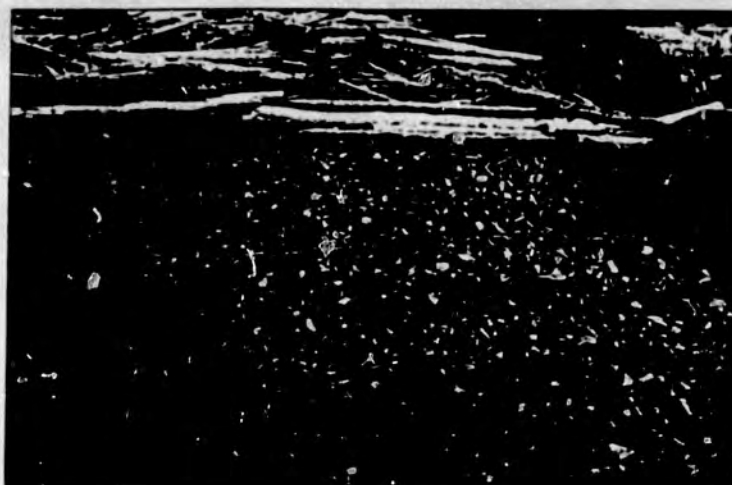
B-7

Photographs B-7 and B-8—
 As in Photographs B-5 and
 B-6, the changes in surface
 oiling are clearly evident
 between May 2, 1989 (B-7)
 and April 10, 1990 (B-8) in
 these views to the east of
 the beach at site AP-1 on
 northeast Smith Island.



B-8

Photographs B-9 and B-10—
 Winter wave action resulted
 in 4 m of lateral erosion and
 1 m of vertical erosion
 between the time of these
 two photographs, which are
 closeup views of the west
 end of the beach at site AP-1
 on northeast Smith Island on
 April 19, 1989 (B-9), and on
 April 10, 1990 (B-10).



B-9



B-10



B-11

Photographs B-11 and B-12—
 Aerial views of Sleepy Bay
 site AP-13 at northern
 Latouche Island show the
 changes in surface oiling
 along the western portion of
 the site from May 9, 1989
 (B-11) to June 12, 1990
 (B-12). The cross indicates
 the location of closeup
 Photographs B-15 to B-16,
 and the arrow locates
 Photographs B-17 and B-18.



B-12

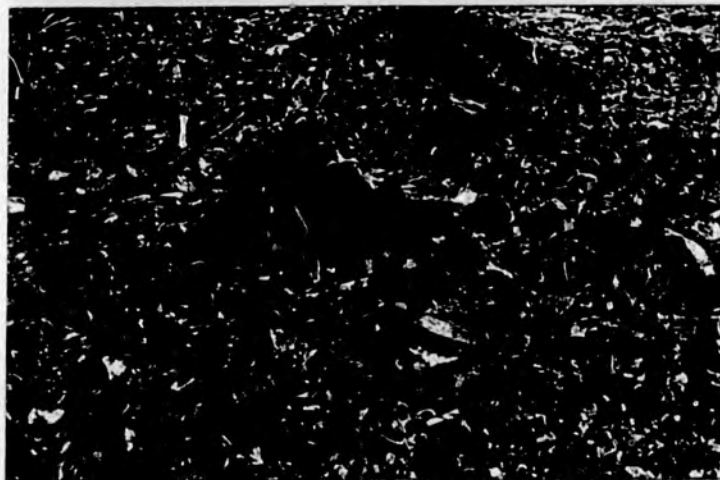
Photographs B-13 and B-14—
 Views of the east end of the
 beach at Sleepy Bay site AP-
 13 at northern Latouche
 Island show the decrease in
 surface oil cover from May
 9, 1989 (B-13) to March 15,
 1990 (B-14).



B-13



B-14



B-15

Photographs B-15 and B-16—
 Closeup photographs of the
 oiled sediments at the east
 end of Sleepy Bay at site
 AP-13 (Photograph B-13)
 show the significant
 changes in oil cover and
 character that occurred
 between May 9, 1989 (B-15)
 and March 15, 1990 (B-16).

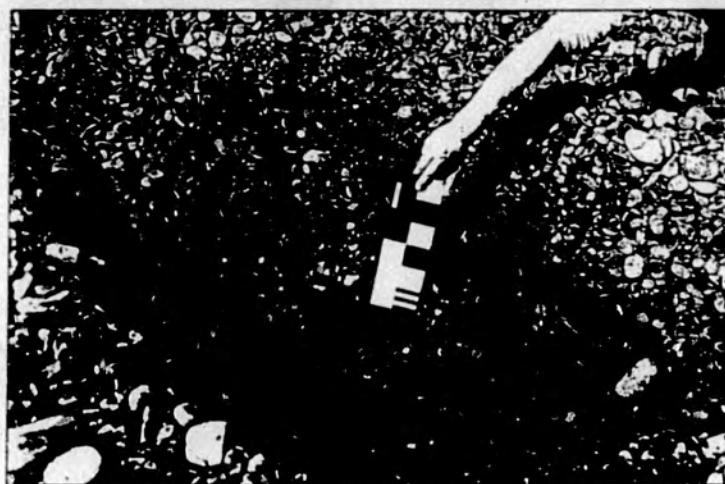


B-16

►
Photographs B-17 and B-18—Pits dug July 13, 1989 (B-17) and June 26, 1990 (B-18) in the same location at Sleepy Bay site AP-13 show changes in subsurface oiling (see Photograph B-12 for location). The dark interval (arrow) is a clean sand layer that limited the downward movement of oil. This sand layer was probably the former seabed, which was elevated during the 1964 Alaska earthquake. The length of the scale is 30 cm (approximately 12 inches). Sketches of these two pits are shown in Figure 9.
►



B-17



B-18

APPENDIX C

Selected Beach Elevation Profiles

Beach profiles were surveyed routinely by measuring elevation changes along transects oriented approximately perpendicular to the shoreline. Measurements were collected usually every 2 m across the beach to the waterline. In most instances, the Emery pole-and-horizon method (Emery 1961) was used to obtain elevation data (Photographs B-3 and B-13, on pages B-2 and B-5). Quality control of the data was achieved by closing the profile; that is, after surveying the transect, the line was resurveyed back to the first point on the profile. Closing errors were normally a few centimeters at most. Fieldwork was timed to coincide with low tides so that most of the intertidal zone at the beach could be surveyed. The graphs contained in this appendix are all plotted on the same height and distance scales, except for sites AK-3 and AK-5. Note the elevation and distance axes are not at the same scale. Elevations are expressed with respect to a local relative datum assumed to be the mean lower low water (MLLW), which is the mean of the lower of the two semi-diurnal tides.

Figure C-1a
Elevation Profile/AP-1, Transect 8

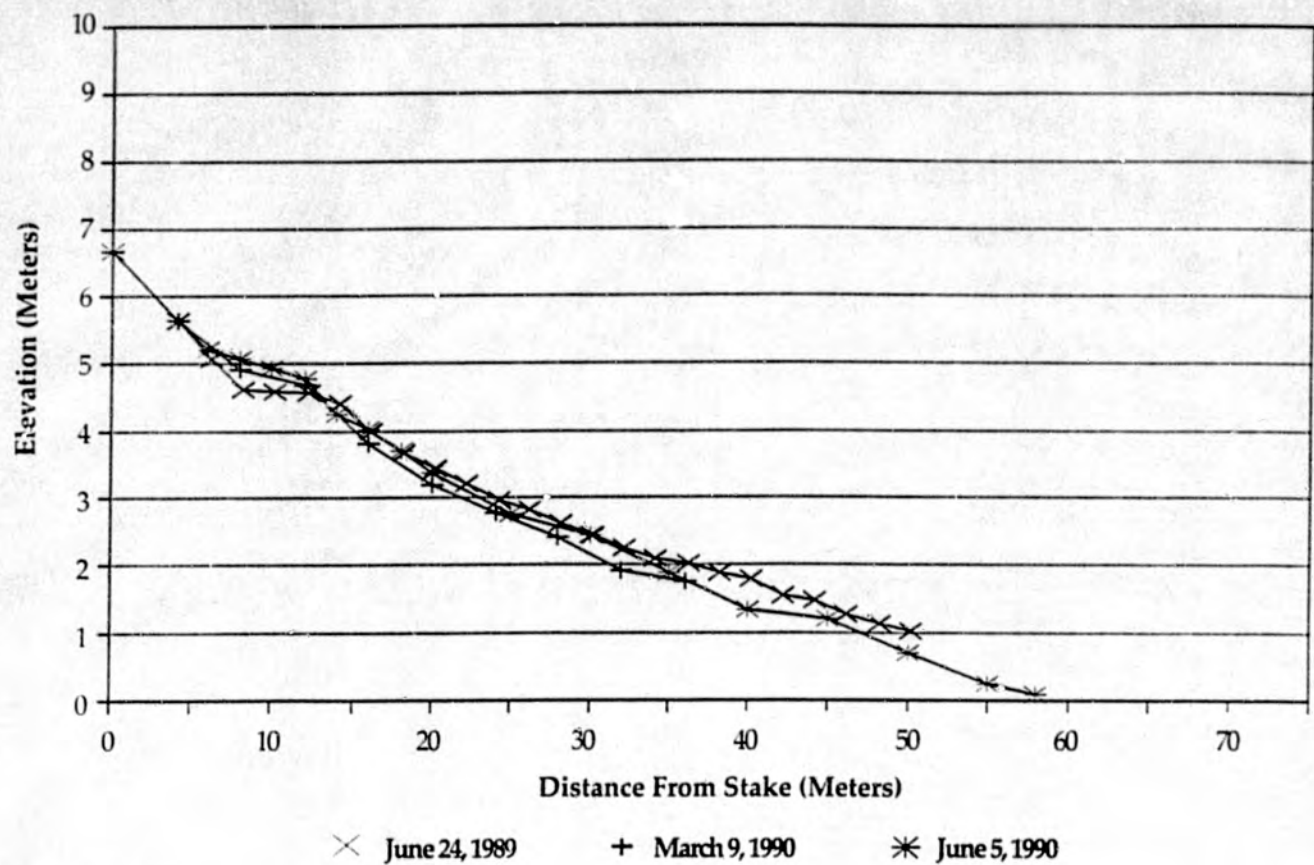


Figure C-1b
Elevation Profile/AP-1, Transect 10

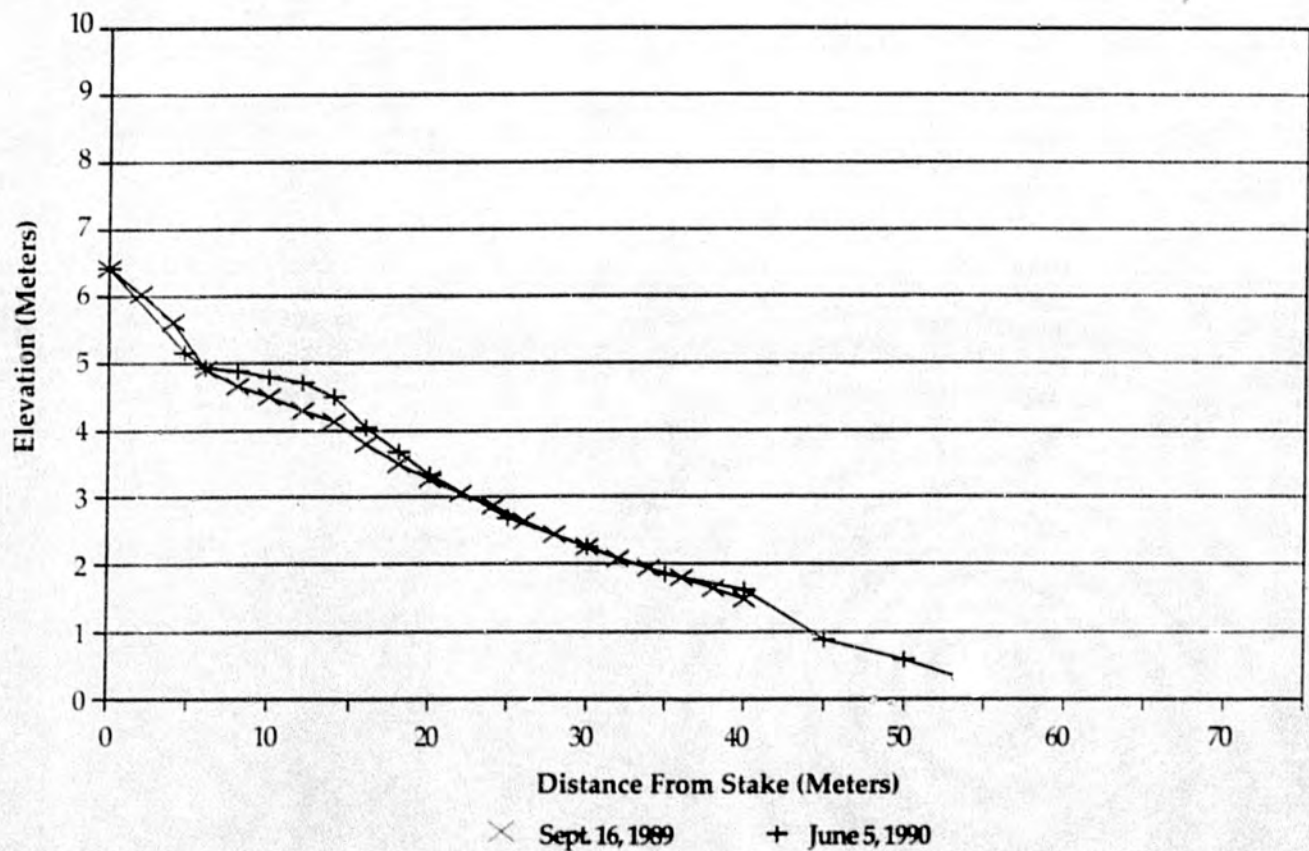


Figure C-2
Elevation Profile/AP-10, Transect 5

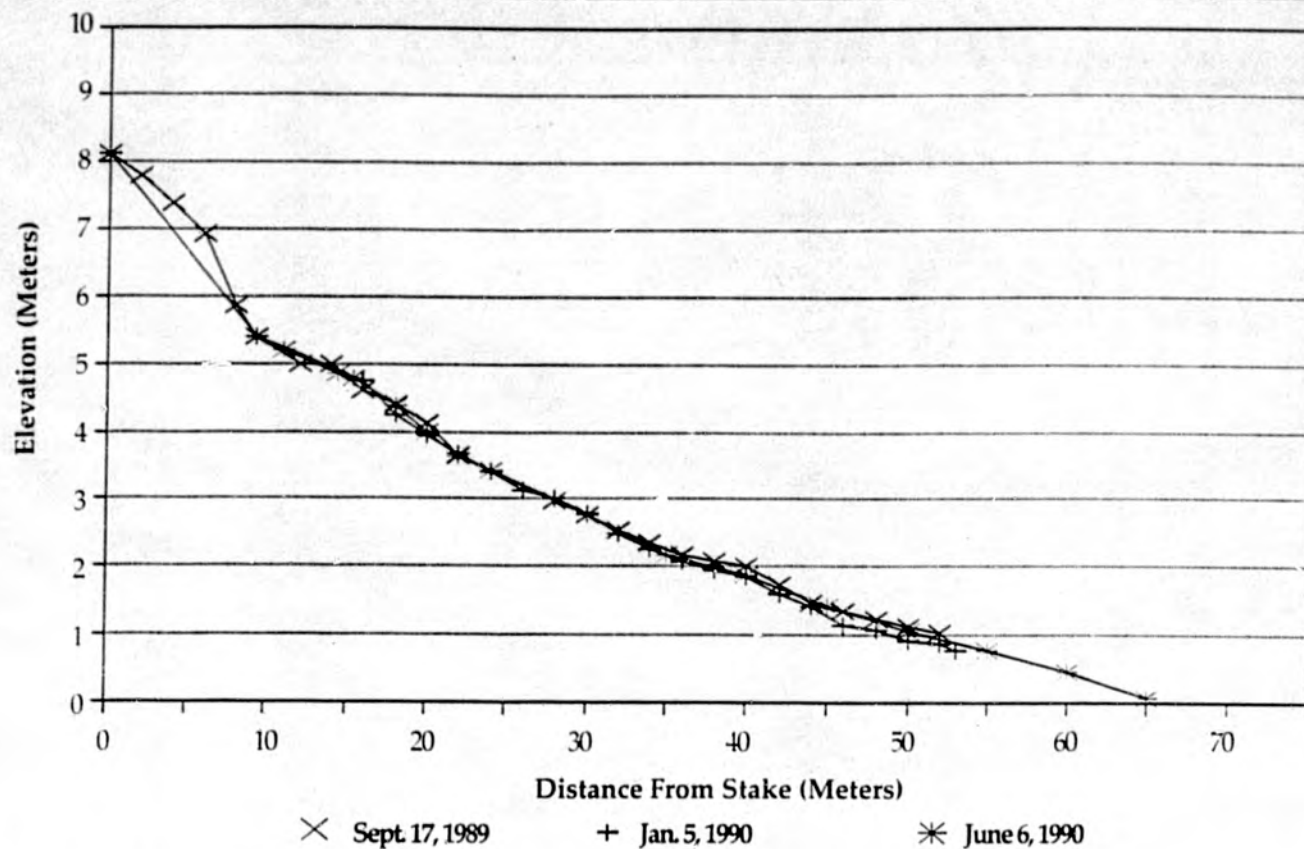


Figure C-3
Elevation Profile/AP-16, Transect 3

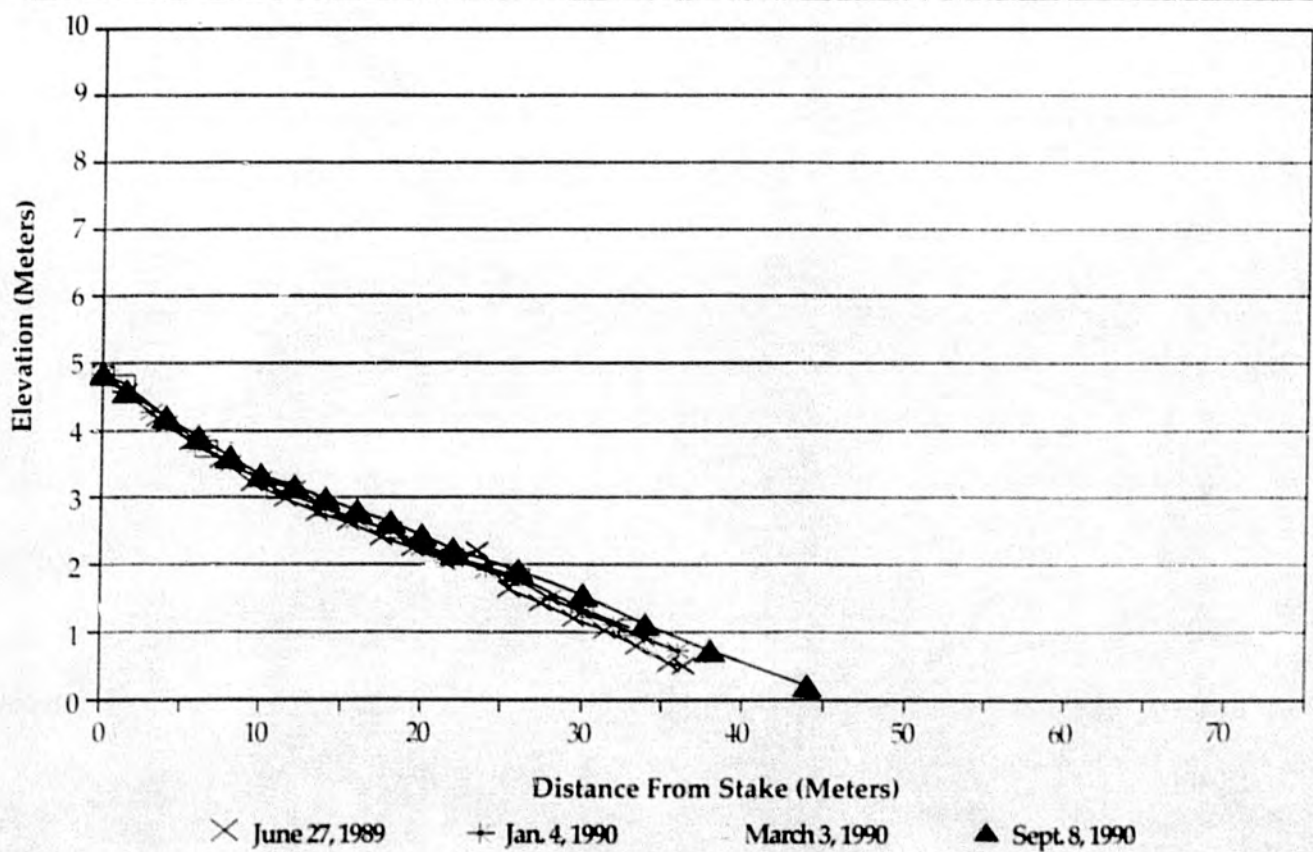


Figure C-4
Elevation Profile/AH-3, Transect 2

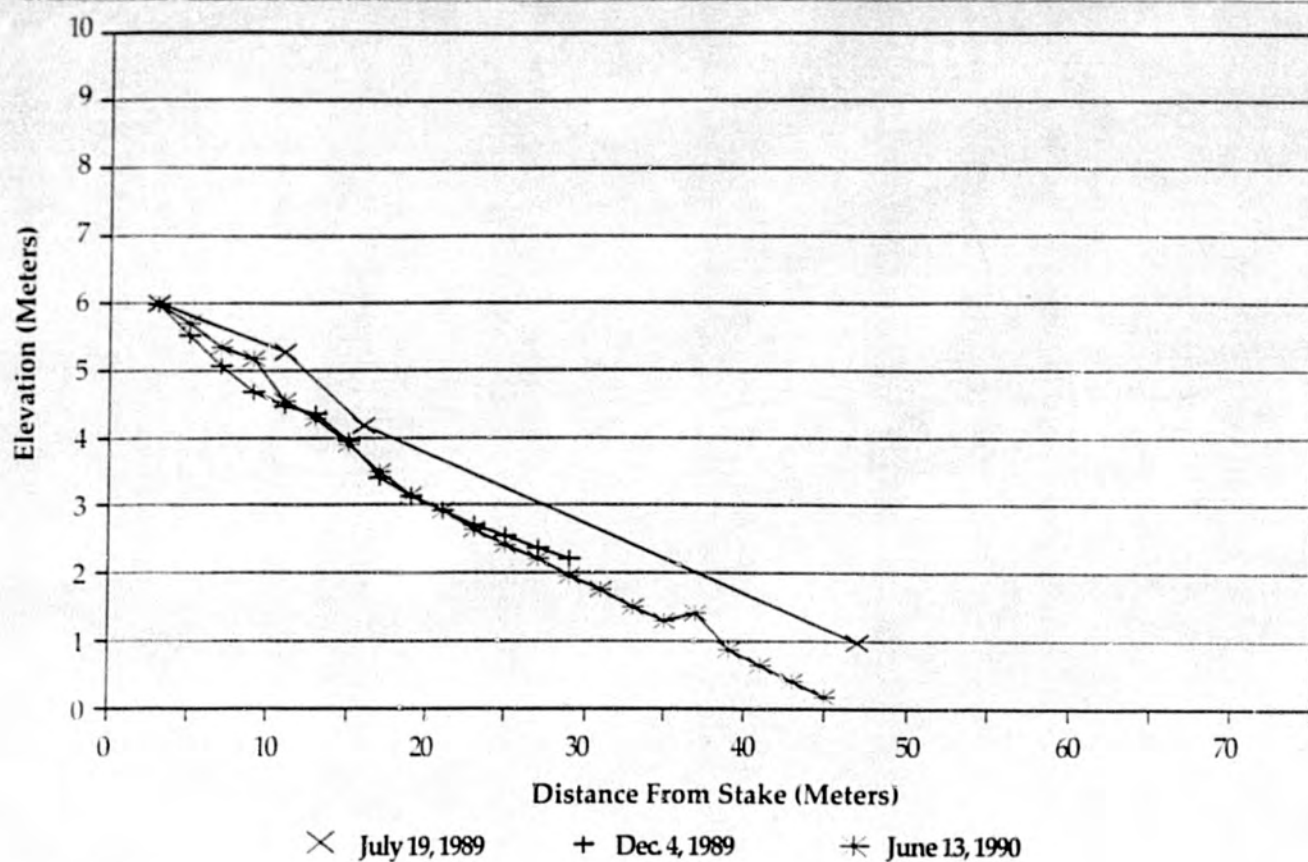


Figure C-5a
Elevation Profile/AK-2, Transect 3

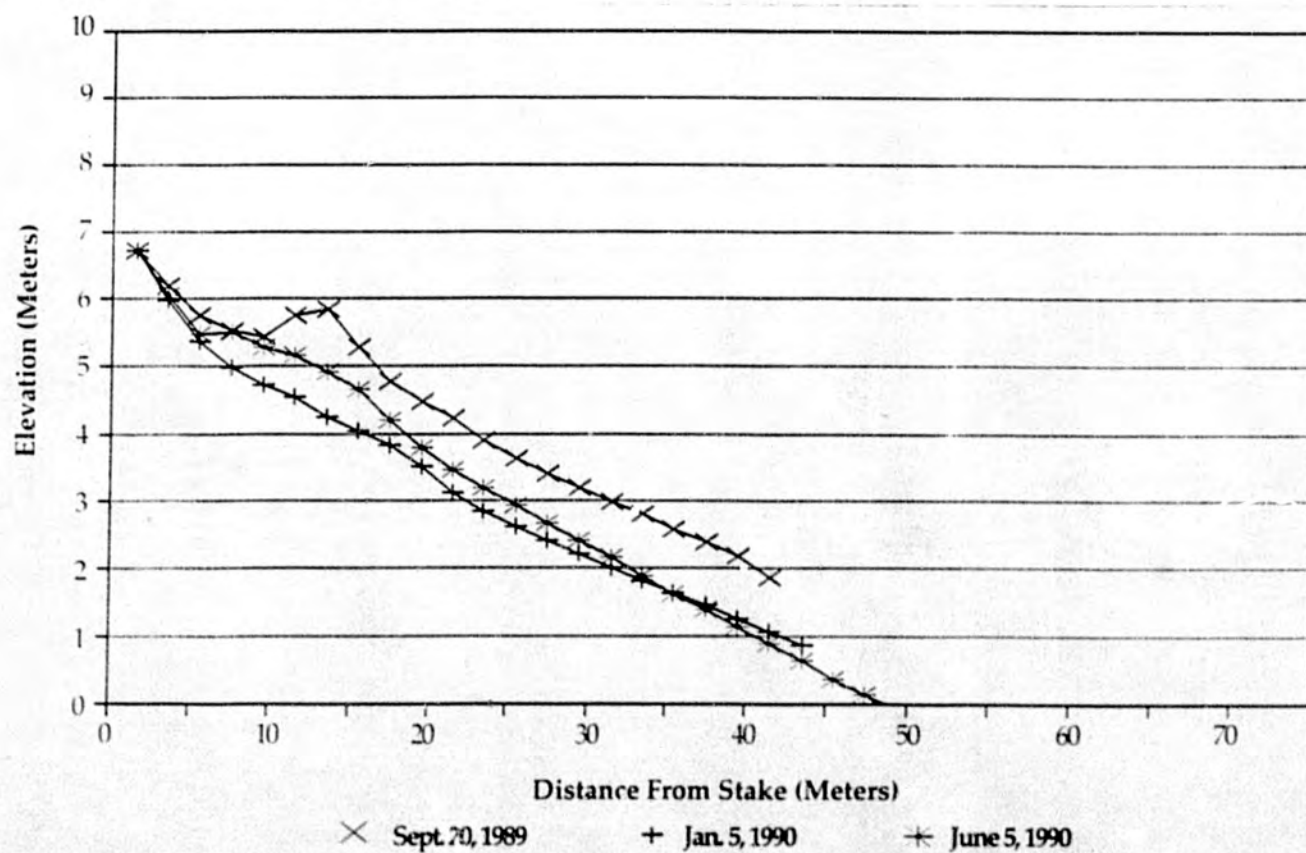


Figure C-5b
Elevation Profile/AK-2, Transect 7

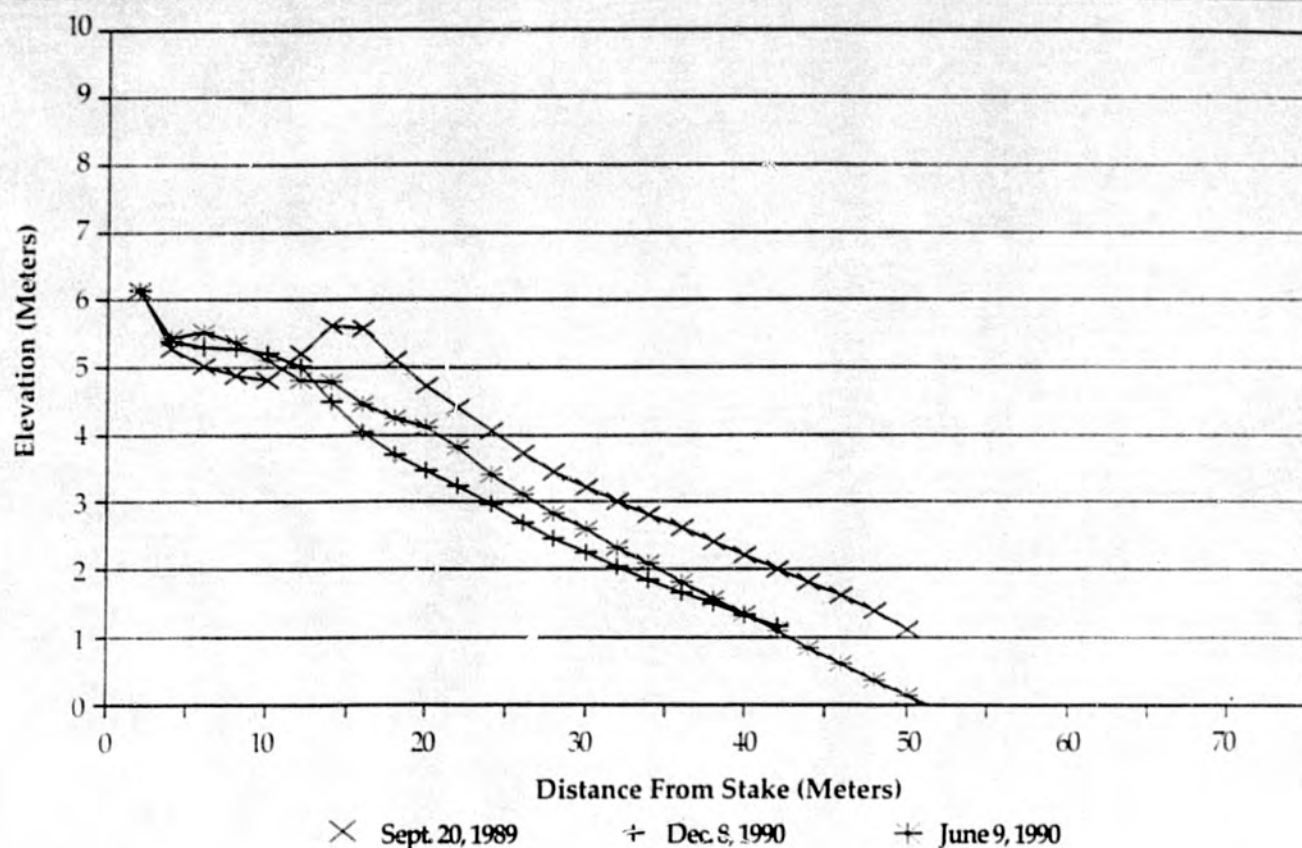


Figure C-6
Elevation Profile/AK-3, Transect 8

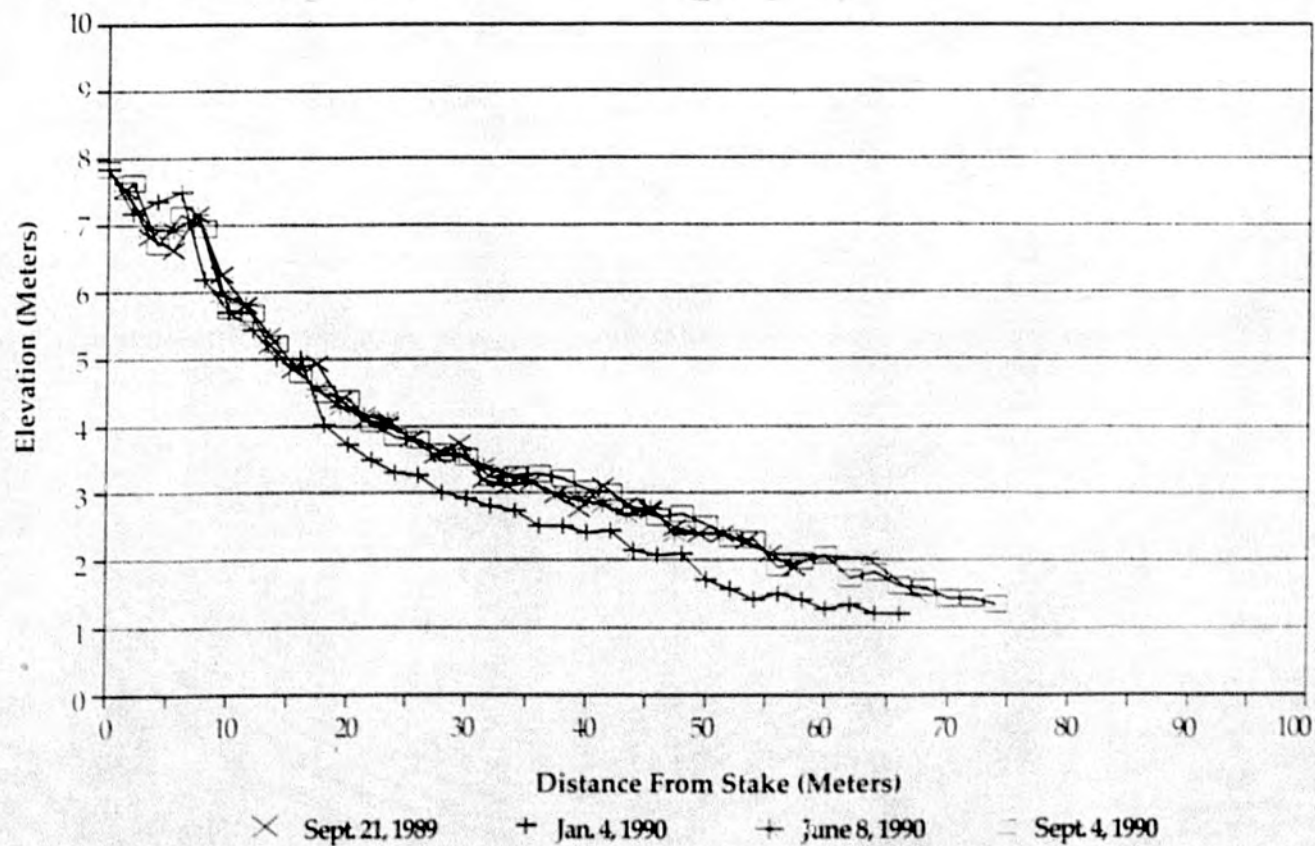


Figure C-7
Elevation Profile/AK-5, Transect 6

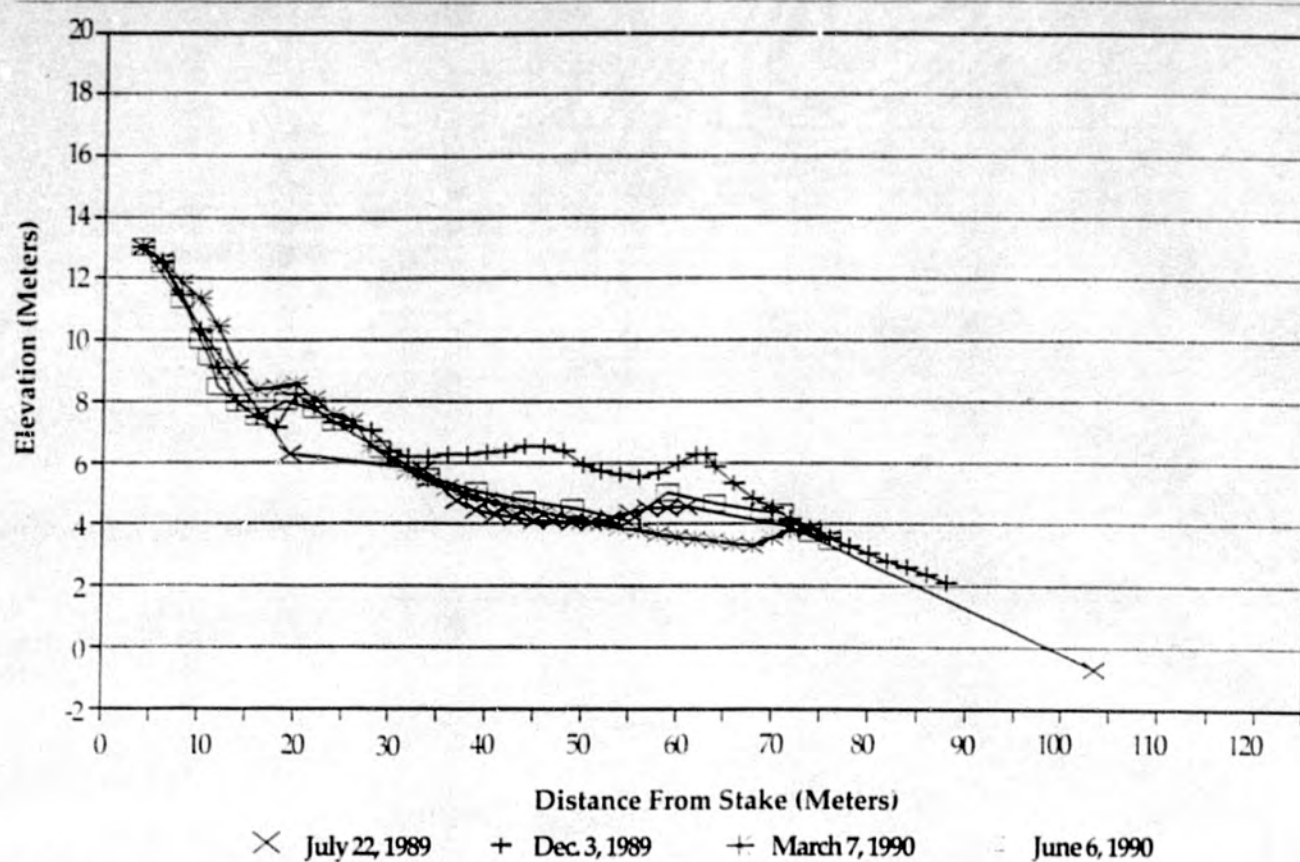
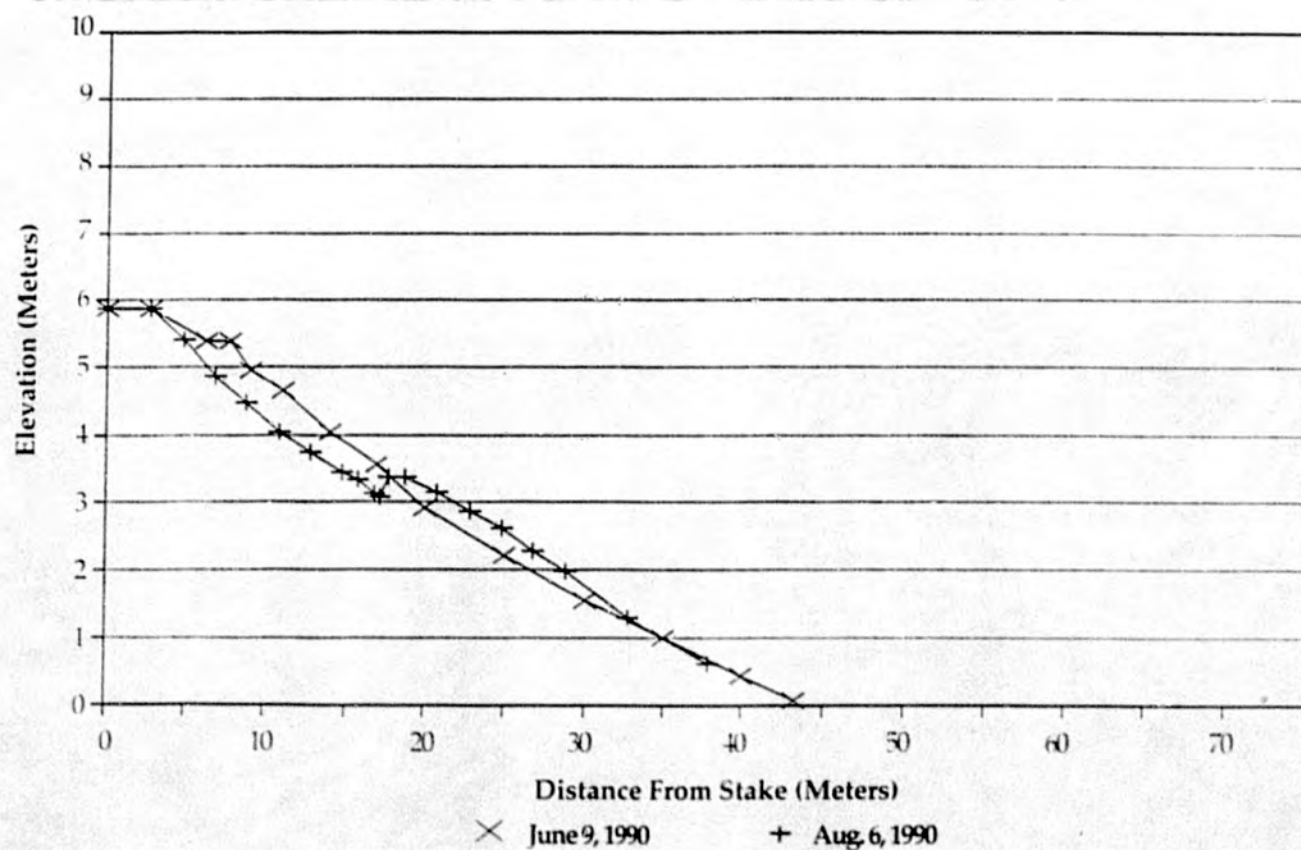


Figure C-8
Pre- and Post-Berm Relocation Profiles/AP-13W, Transect 26



APPENDIX D

Surface Oil Cover Data

This appendix provides data on the observed changes in surface oil cover for each of the primary surveyed sites. All survey dates are given in Table D-1 and the "equivalent oiled area" values in Table D-2, both on the next two pages. The "percent oiled area" values (the equivalent oiled area divided by the total oiled area) for each beach are presented in Table 6, on page 21. Site locations are indicated on the maps in Appendix A.

Maps indicating changes in surface oil cover are shown for selected sites discussed in the text. Surface oil cover data were collected along the transects shown as numbered solid lines crossing the beaches. In cases where data were not collected during a given survey, the transect lines are dashed. Surface oil cover is expressed as a percent of the total observed beach surface and is interpolated between transects. Field observations of surface oil cover were made to the nearest 5 percent, and these values have been grouped into five categories on the maps for illustration purposes. The shoreline at each site is approximated by the mean high water (MHW) line.

Table D-1
Oil Cover Survey Dates

SITE	1989							1990			
AP-1	-	6/24	8/29	9/16	10/15	11/10	12/4	-	3/9	6/5	9/2
AP-2	-	6/23	8/29	9/20	10/14		12/4	1/2		6/5	9/3
AP-3	5/17	7/6	8/28	9/21	-	11/11	-	-		-	-
AP-4	-	-	8/22	9/15	10/15		12/4	1/9	3/1	6/10	9/3
AP-5	5/15	7/6	8/23	-	10/19		12/3	-	3/2	6/6	-
AP-6	-	-	8/21	9/16	10/19		-	1/2	3/2	6/5	9/1
AP-7	-	7/2	8/19	9/20	10/18		-	1/6	3/6	6/12	-
AP-8	-	7/2	8/19	9/20	10/18	11/10	-	1/6	3/6	6/12	9/1
AP-9	-	7/5	8/16	-	-		-	-	3/3	-	-
AP-10	-	7/5	8/16	9/17	10/16		-	1/5	3/3	6/6	9/5
AP-11	5/12	6/17	8/17	9/19	10/17		-	-	3/3	6/13	-
AP-12	5/12	6/17	8/15	9/19	10/20	11/7	12/5	1/7	3/6	6/9	9/9
AP-13E	5/9	6/16	8/14	-	-		12/8	-	3/4	6/8	9/4
AP-13C	5/10	6/16	8/14	-	10/20		12/8	-	3/4	6/8	9/4
AP-13W	5/11	6/17	8/14	-	10/17	11/7	-	1/4-5	3/4	6/9	9/4
AP-14	5/16	6/18	8/14	9/20	-		12/7	1/6	3/7	6/13	9/2
AP-15	-	6/28	8/27	-	-		-	-	3/3	6/7	9/3
AP-16	-	6/27	8/10	9/18	10/19		12/14	1/4	3/3	6/7	9/8
AP-17	-	6/26	8/8	9/18	10/19		12/5	1/5	3/3	6/7	-
AP-18	-	6/26	8/9	9/17	10/16		12/5	1/4	3/3	6/7	9/3
AH-1	-	7/25		9/17	10/17	11/10	12/5	-	3/3	6/11	-
AH-2	-	7/18		9/15	10/17	11/10	12/5	-	3/8	6/11	9/8
AH-3	-	7/19		9/22	10/15	11/8	12/4	1/2	3/3	6/13	-
AH-4	-	7/19		9/16	10/15	11/8	12/4	1/2	3/8	6/12	-
AK-1	-	-	8/4	9/20	10/18	11/13	12/8	1/5	3/3*	6/7	9/2
AK-2	-	7/31		9/20	10/18	11/13	12/8	1/5	3/3	6/9	-
AK-3	-	-	8/1	9/21	10/19	11/15	-	1/4	3/4	6/8	9/4
AK-4	-	-	8/4	9/21	10/19	11/15	-	1/4	3/4	6/8	-
AK-5	-	7/22		-	10/14		12/3	-	3/7	6/6	9/7
AS-1	-	-		-	10/16	11/11	12/7	1/3	3/8*	6/5	9/1

Note: Site AP-13 was subdivided into three sections (East, Central and West) but is considered as a "single" site in most instances.

- Site not visited.

* Site visited but no measurement taken.

Table D-2

Oil Cover Surveys / Equivalent Oiled Area Data (Square Meters)

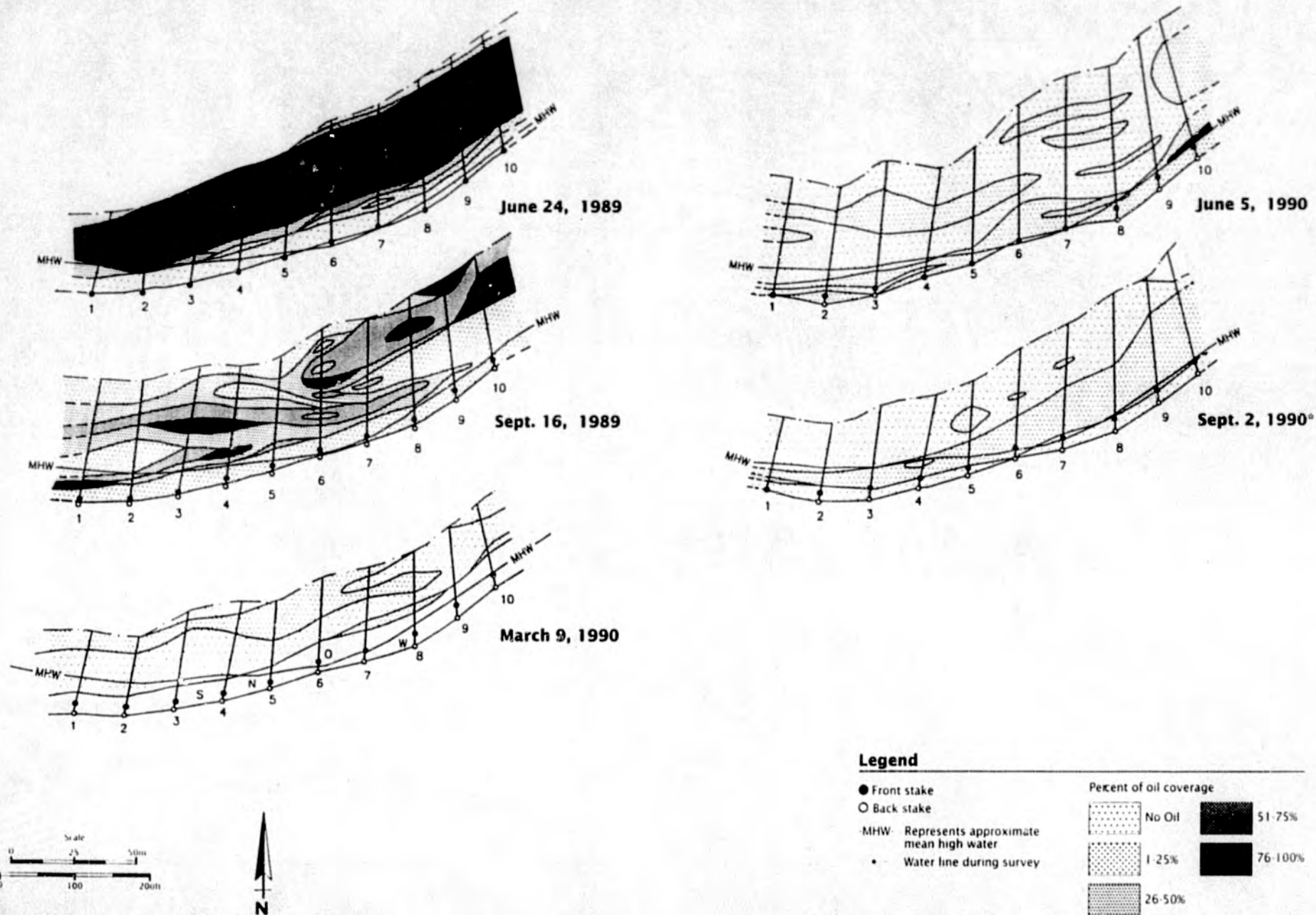
SITE	5/89	6-7/89	8/89	9/89	10/89	11/89	12/89	1/90	3/90	6/90	9/90
AP-1	-	1,565	827	386	357	238	77	-		49	40
AP-2	-	1,073	852	614	644		518	180		181	97
AP-3	204	191	119	119	-		-	-		-	-
AP-4	-	-	507	535	416		387	118		55	27
AP-5	959	364	405	-	67		153	-		38	-
AP-6	-	-	120	124	68		-	48		28	6
AP-7	-	220	183	199	184		-	83		51	-
AP-8	-	962	789	795	285		-	302		134	93
AP-9	-	1,151	1,003	-	-		-	-		-	-
AP-10	-	996	951	877	363		-	438		126	78
AP-11	504	509	477	530	123		-	-		10	-
AP-12	2,037	1,549	1,863	740	455	474	864	496		204	878
AP-13E	1,177	935	818	-	-		368	-	703	81	28
AP-13C	734	872	1,074	-	725		695	-		260	470
AP-13W	536	300	604	-	38		-	3		13	40
AP-14	756	789	596	352	-		311	130		115	10
AP-15	-	605	212	-	-		-	-		19	6
AP-16	-	411	281	228	135		9	30		22	11
AP-17	-	348	179	243	103		34	27		5	-
AP-18	-	690	434	393	98		129	53		49	28
AH-1	-	39		51	0	18	0	-		0	-
AH-2	-	614		918	166	11	110	-		1	22
AH-3	-	0		10	0	0	3	0.4		0	-
AH-4	-	204		192	99	18	3	1.6		1	-
AK-1	-	-	366	317	51		56	66		37	42
AK-2	-	46		16	6		0	0		0	-
AK-3	-	-	175	189	395		-	102		131	67
AK-4	-	-	507	580	43		-	33		17	-
AK-5	-	451		-	283		487	-		27	237
AS-1	-	-		-	360	351	308	330		246	68

Note: Site AP-13 was subdivided into three sections (East, Central and West) but is considered as a "single" site in most instances.

- Site not visited.

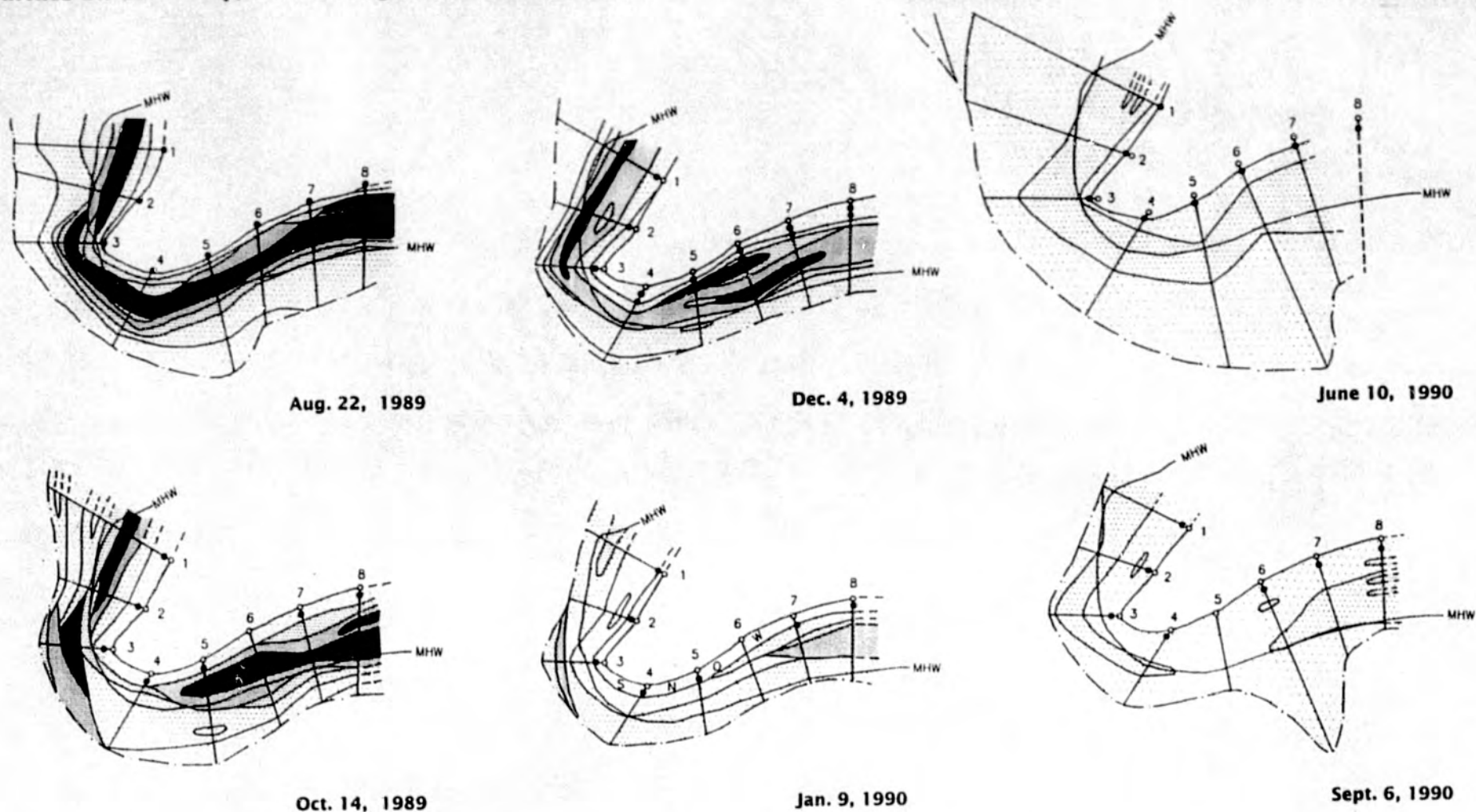
* Site visited but no measurement taken.

Figure D-1
Surface Oil Cover Map/Northeast Smith Island, Site AP-1



*After 1990 berm relocation

Figure D-2
Surface Oil Cover Map/Foul Pass - Ingot Island, Site AP-4



Legend

- Front stake
- Back stake

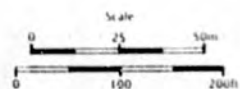
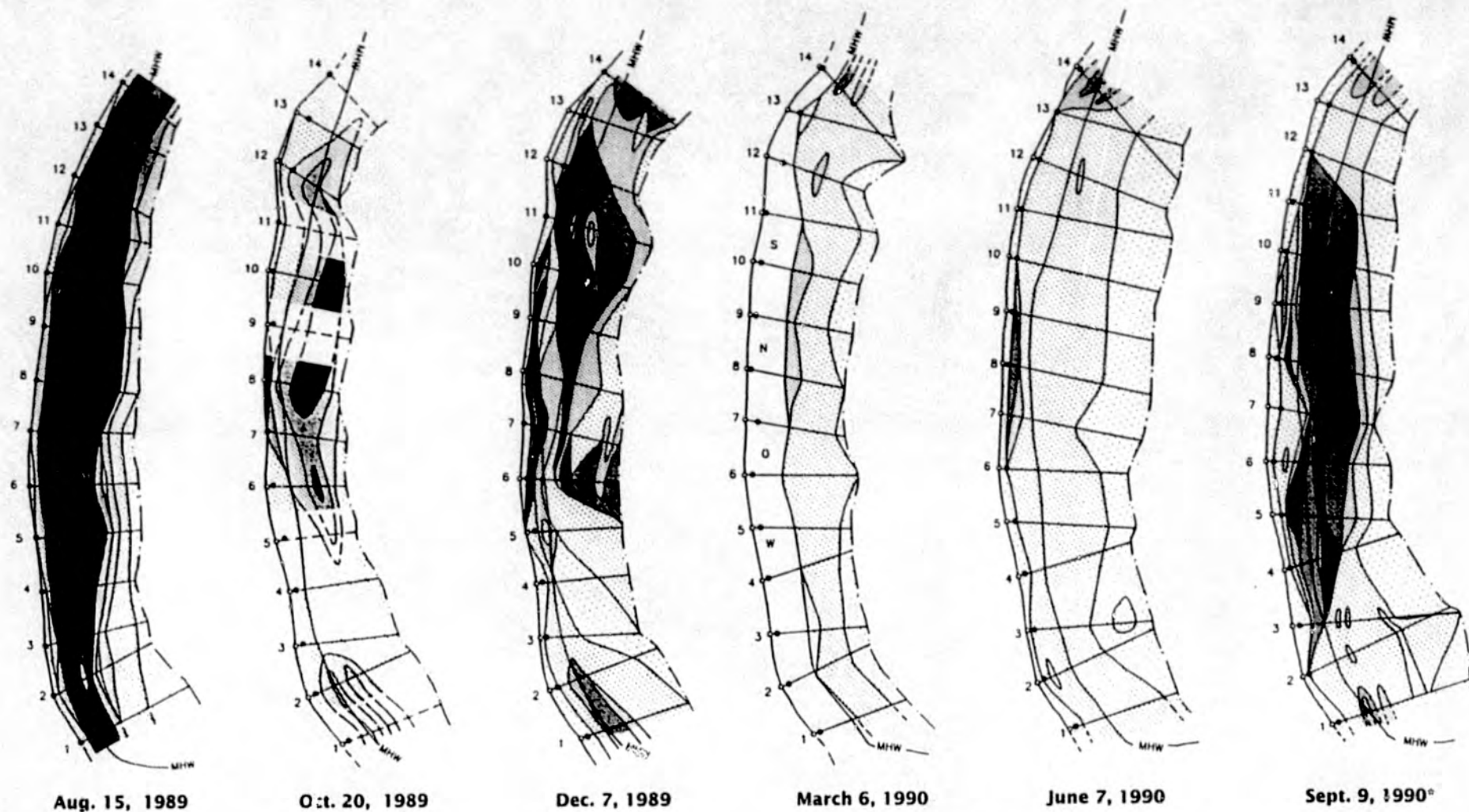
MHW Represents approximate mean high water

--- Water line during survey

Percent of oil coverage

No Oil	51-75%
1-25%	76-100%
26-50%	

Figure D-3
Surface Oil Cover Map/Northeast Latouche Island - North, Site AP-12



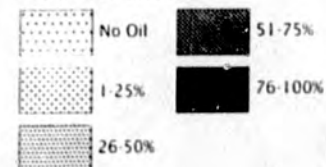
Legend

- Front stake
- Back stake

MHW: Represents approximate mean high water

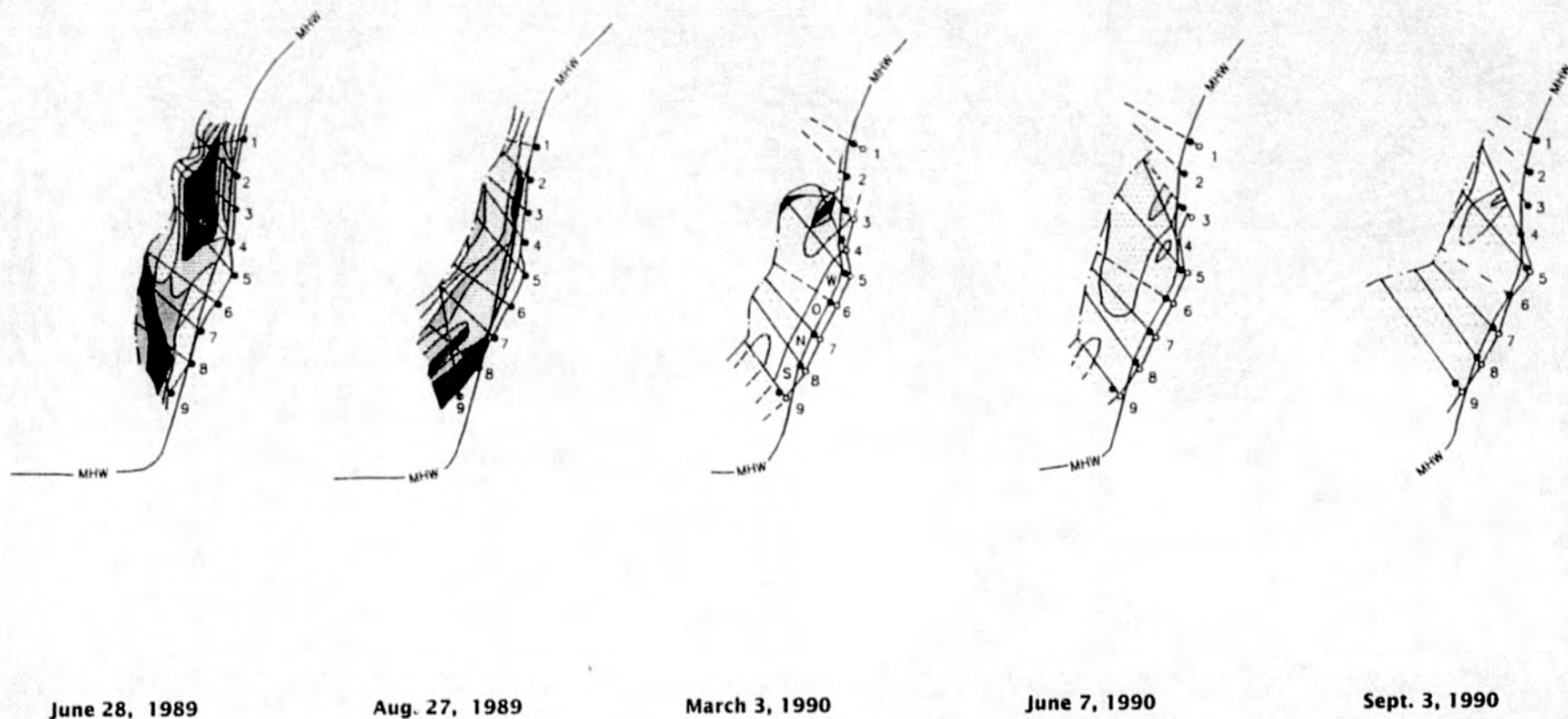
- Water line during survey

Percent of oil coverage



*After 1990 berm relocation.

Figure D-4
Surface Oil Cover Map/North Evans Island, Site AP-15



Legend

- Front stake
- Back stake
- MHW Represents approximate mean high water
- Water line during survey

Percent of oil coverage

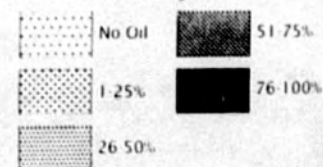
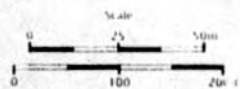
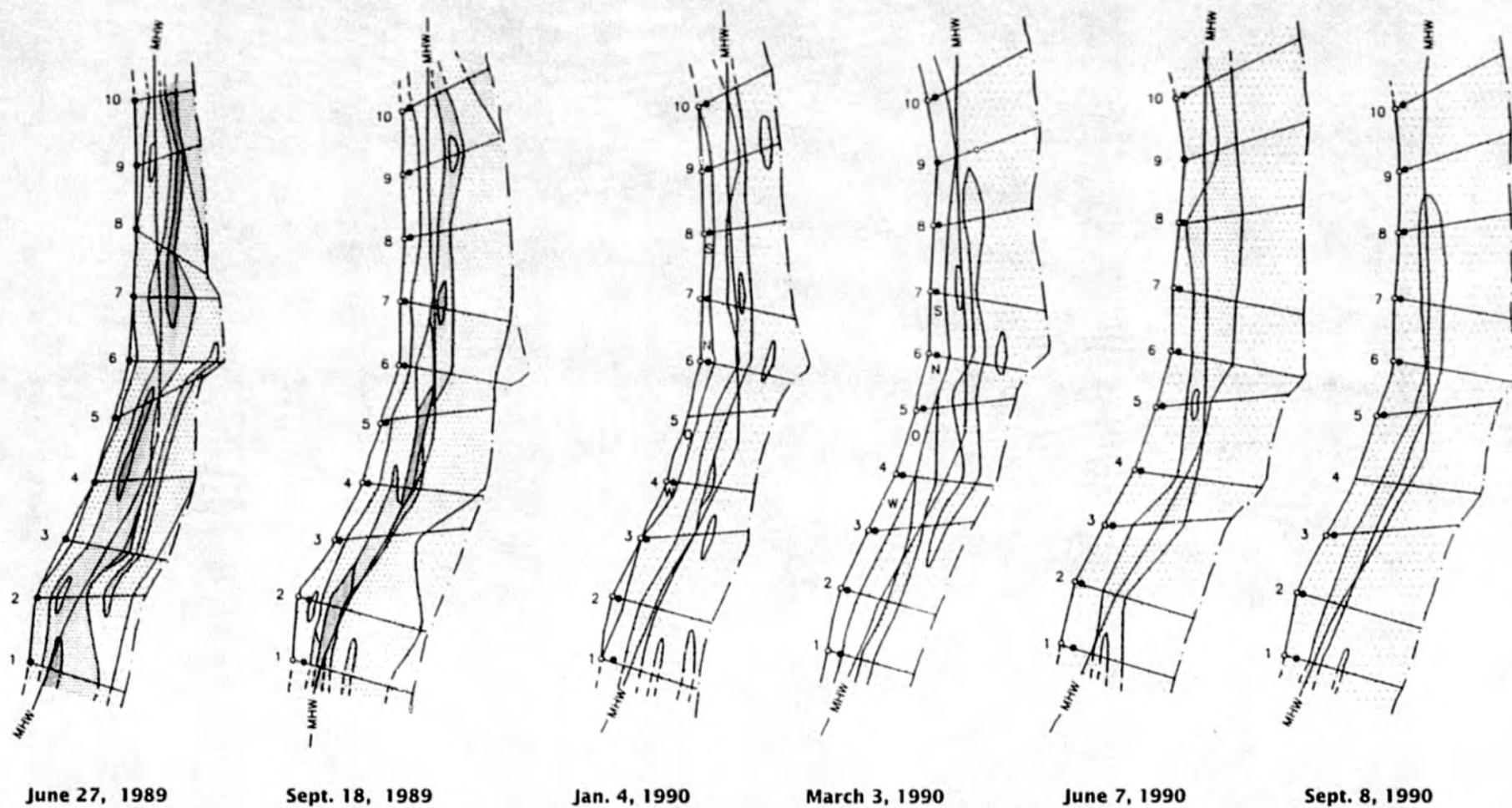


Figure D-5
Surface Oil Cover Map/Southwest Elrington Island - East, Site AP-16



Legend

- Front stake
- Back stake
- MHW Represents approximate mean high water
- Water line during survey

Percent of oil coverage

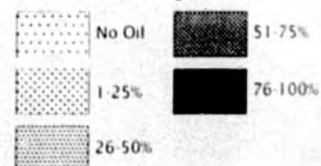
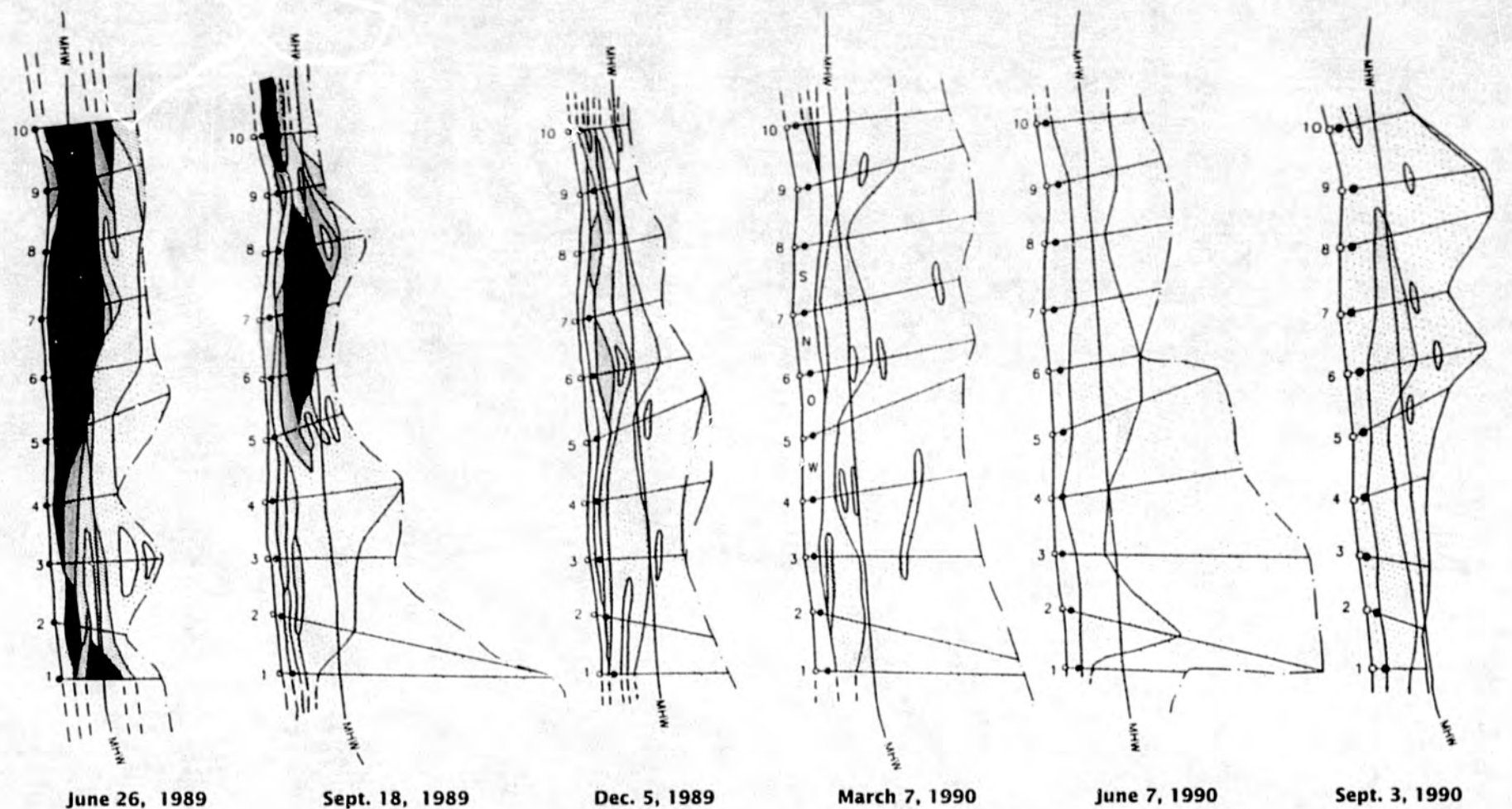


Figure D-6
Surface Oil Cover Map/Southwest Eltrington Island - Southwest, Site AP-18



Legend

- Front stake
- Back stake
- MHW Represents approximate mean high water
- Water line during survey

Percent of oil coverage

No Oil	51-75%
1-25%	76-100%
26-50%	



D-10 Figure D-7
Surface Oil Cover Map/North Windy Bay, Site AH-2

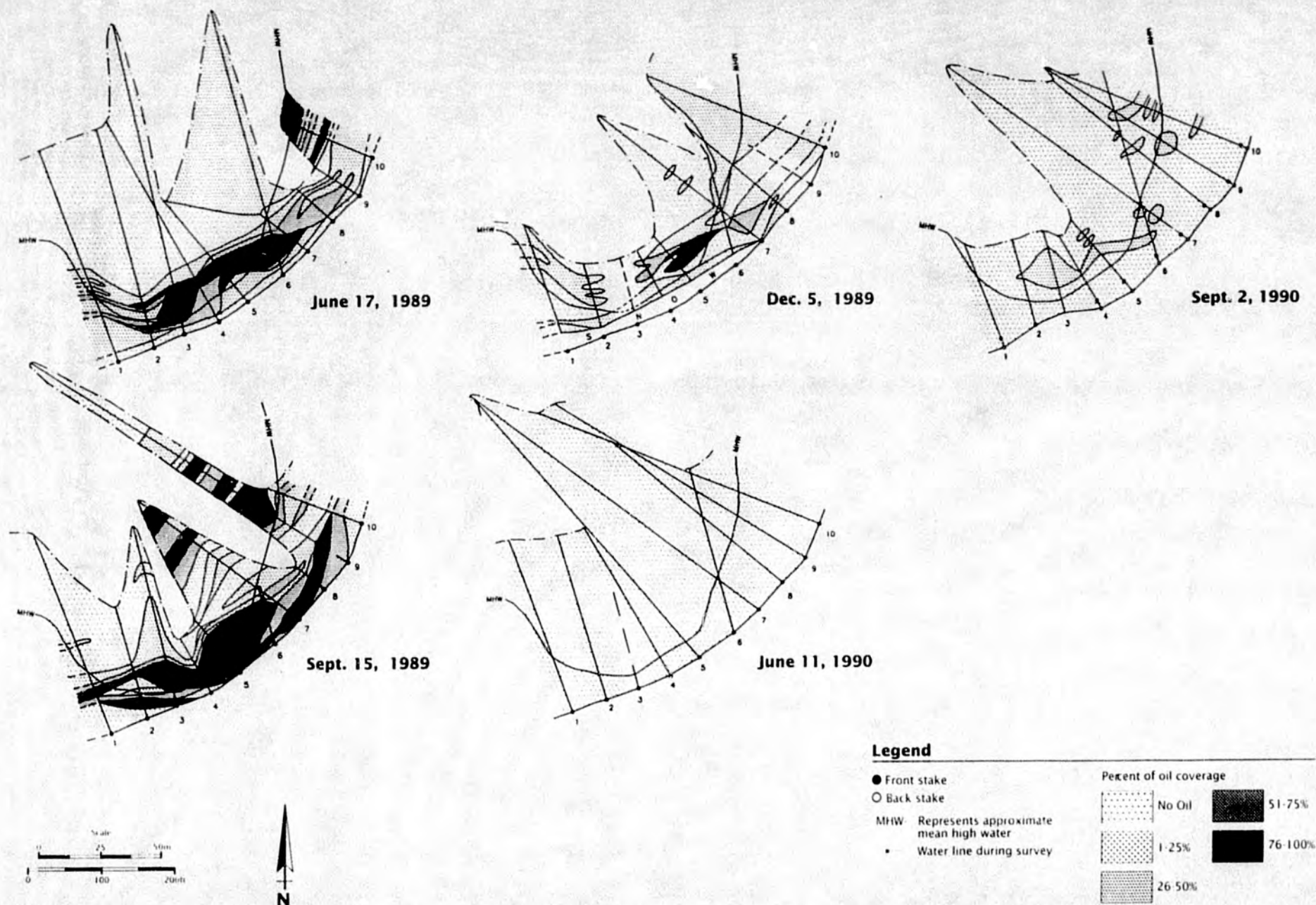
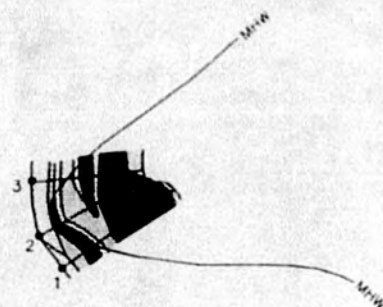
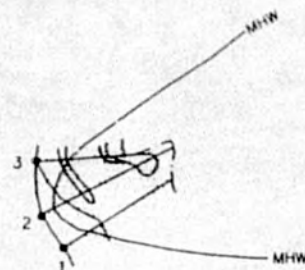


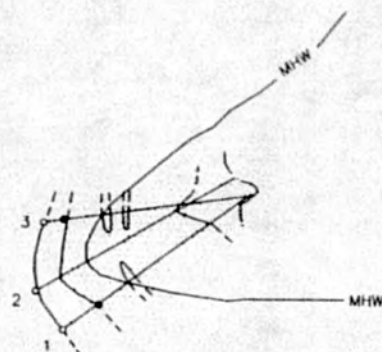
Figure D-8
Surface Oil Cover Map/Perevalnie Point, Site AK-1



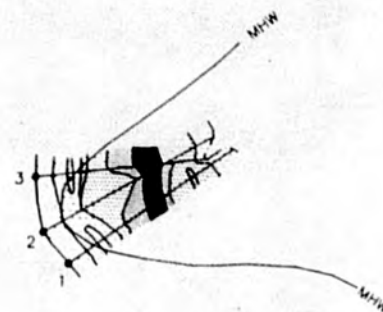
Aug. 4, 1989



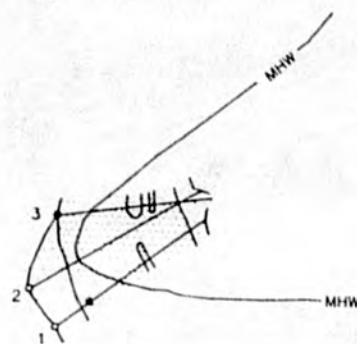
Nov. 13, 1989



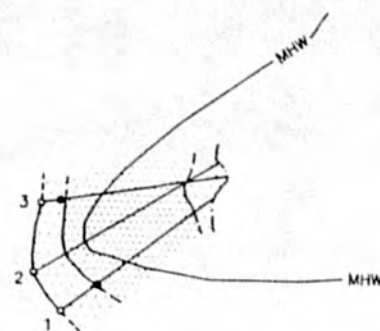
June 7, 1990



Sept. 20, 1989



Jan. 5, 1990



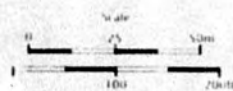
Sept. 2, 1990

Legend

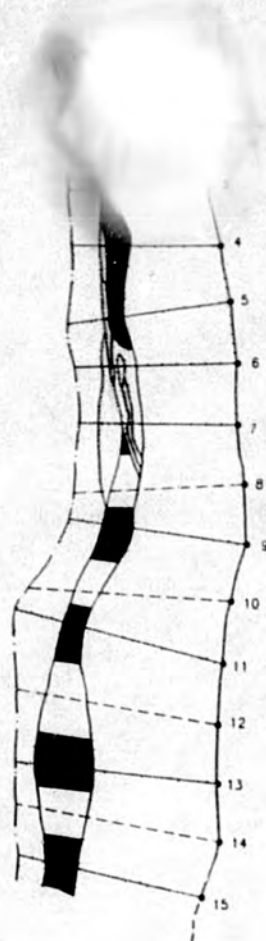
- Front stake
- Back stake
- MHW: Represents approximate mean high water
- Water line during survey

Percent of oil coverage

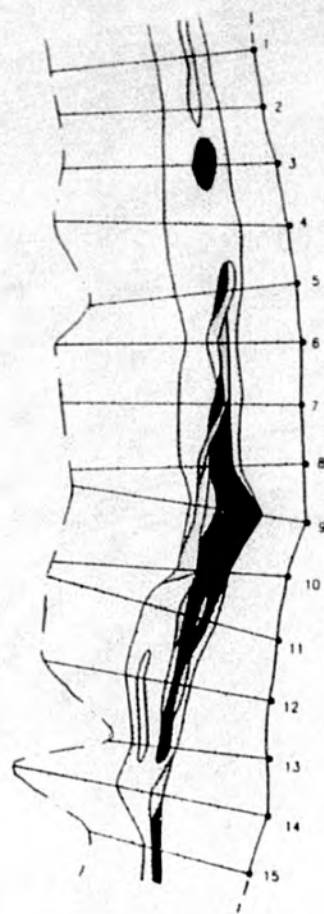
No Oil	51-75%
1-25%	76-100%
26-50%	



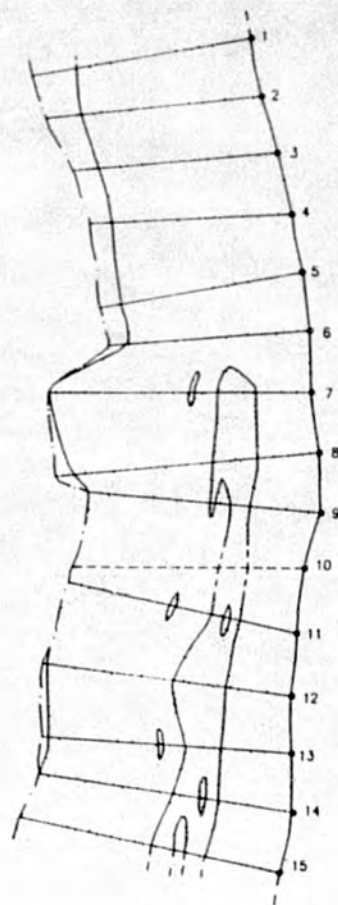
D-12 Figure D-9
Surface Oil Cover Map/Ushagat Island, Site AK-5



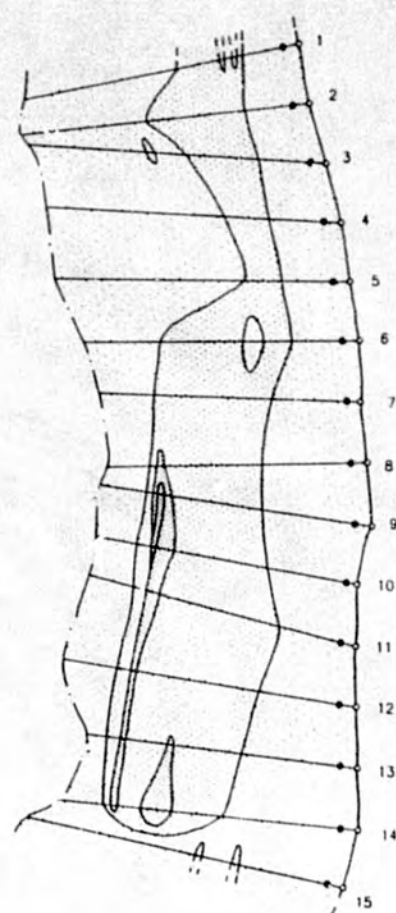
July 24, 1989



Dec. 3, 1989



June 6, 1990



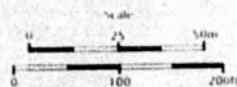
Sept. 7 & 10, 1990*

Legend

- Front stake
- Back stake
- MHW Represents approximate mean high water
- Water line during survey

Percent of oil coverage

No Oil	51-75%
1-25%	76-100%
26-50%	



*After 1990 berm relocation.

APPENDIX E

Seal Island Wind Data

The Seal Island wind data (obtained from the National Oceanic and Atmospheric Administration) provide a picture of winter conditions for the sites in Prince William Sound near the center of the study area (Figure 3, on page 7). The data are not directly affected by the bursts of cold dense air (katabatic winds) that occasionally spill over the coastal mountains during winter. These katabatic winds provide a different wind regime at stations, such as Port Valdez, in the north of the Sound.

Seal Island Wind Data

Wind data for Seal Island are illustrated in Figures E-1a and E-1b, on pages E-4 and E-5. During the winter months (September 1989 to April 1990), the Sound had six major storms and 12 storms of lower intensity (Tables E-1 and E-2, on the next page). The distinction between the two categories is based on wind speed, duration, and the directional consistency of the winds for a sustained period of time.

The major storms were:

Oct. 4-8, 1989:	out of the SE for 5 days
Oct. 15-21, 1989:	out of the SE through NW for 7 days
Nov. 6-10, 1989:	out of the N for 5 days
Nov. 21-23, 1989:	out of the SE for 3 days
Dec. 1-12, 1989:	out of the NE through SE for 12 days
Dec. 27-31, 1989:	out of the SE through NW for 5 days

These storm winds generated waves primarily from eastern directions with a secondary northern component.

The lower intensity storms occurred in the second half of the winter, with three in both January and February 1990. These storms had winds primarily out of the NW to NE and out of the NE to SE (Table E-2, on the next page).

Table E-1
Major Storms

Dates	Maximum Average Wind Speed (km/h)	Peak Wind Speed (km/h)	Direction	Dates of Spring Tides > 4 meters*
Oct. 4-8, 1989	43	88	Southeast-Southwest	-
Oct. 15-21, 1989	60	93	East-Southeast-North-Northwest	Oct. 15-19
Nov. 6-10, 1989	60	85	Northwest-North	Nov. 10
Nov. 21-23, 1989	51	135	East-Southeast	-
Dec. 1-12, 1989	48	111	Northeast-Southeast	Dec. 9-12
Dec. 27-31, 1989	52	111	Southeast-Southwest-Northwest	Dec. 27-30

- Predicted high water levels < 4 m.

* Predicted spring high water levels at Cordova.

Table E-2
Secondary Storms

Dates	Maximum Average Wind Speed (km/h)	Peak Wind Speed (km/h)	Direction	Dates of Spring Tides > 4 meters*
Sept. 23-24, 1989	41	98	Southeast	-
Oct. 25-28, 1989	38	87	Northwest-Southeast	-
Dec. 24-25, 1989	52	111	Southeast-Southwest	-
Jan. 8-11, 1990	37	80	Northwest-East	Jan. 8-11
Jan. 17-19, 1990	31	63	Northwest-North	-
Jan. 29-31, 1990	32	61	North-Northeast	Jan. 29-31
Feb. 5-8, 1990	38	63	North	Feb. 7-8
Feb. 13-14, 1990	39	70	Northeast-South	-
Feb. 26-27, 1990	40	80	West-Northwest	Feb. 26-27
March 6-8, 1990	36	61	Southeast-Northwest	-
March 26-28, 1990	40	82	East	March 26-28
April 3-5, 1990	31	87	West	-

- Predicted high water levels < 4 m.

* Predicted spring high water levels at Cordova.

Figure E-1a
Seal Island Wind Data / September 1989 to June 1990

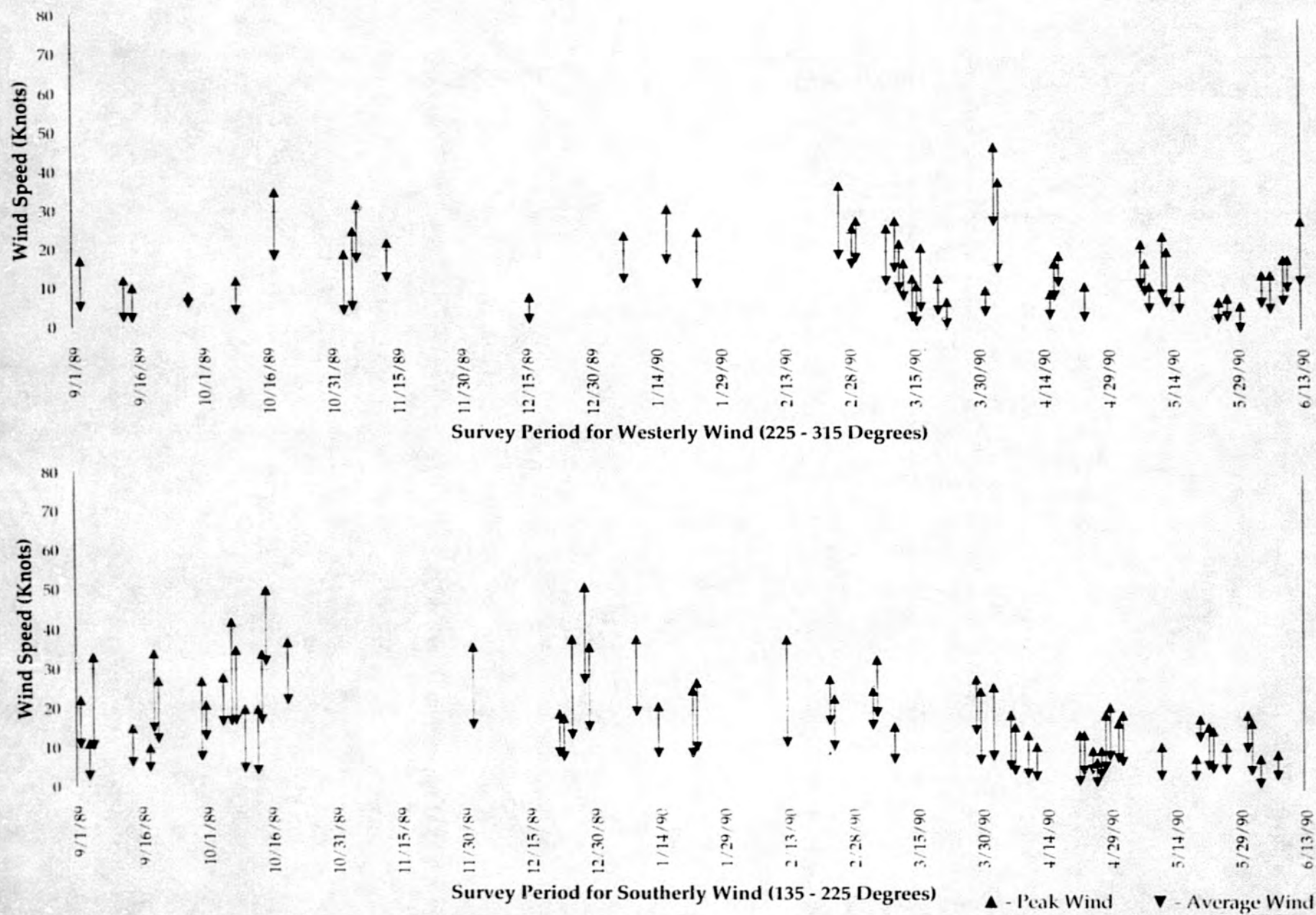
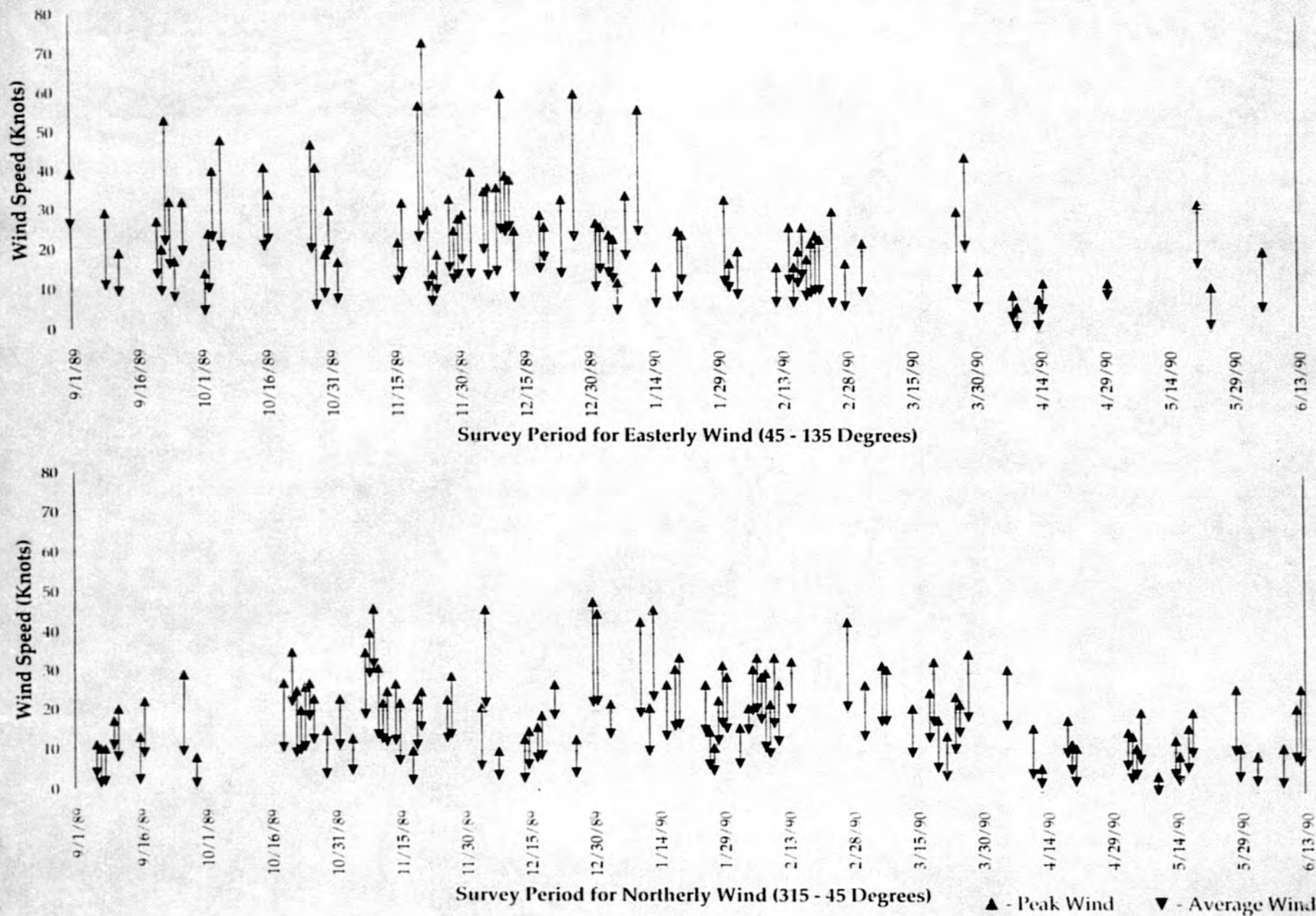


Figure E-1b

Seal Island Wind Data / September 1989 to June 1990



APPENDIX F

Winter Breaker Height Data

Time-lapse photography surveys provided a nearly continuous record of coastal processes and beach changes at five sites in the Sound during daylight hours from mid-November 1989 to mid-April 1990. In addition to three long-term monitoring sites, two other sites (Bay of Isles and Chenega Island) were added to the time-lapse photography surveys. As a group, they represent the various wave-energy environments in the Sound.

Photographs from the Sleepy Bay site appear on pages F-11 and F-12. They represent some of the observed variations at this exposed location.

Winter Breaker Height Data

One component of the image analysis involved an estimate of breaker height. Data from this analysis are summarized as a series of figures (F-1 through F-5) that show the averaged daily breaker height and, at three of the five sites, illustrate when predicted high tides at Cordova exceeded 4 m (Table F-1).

Table F-1
Predicted Spring Tides at Cordova

Periods of Predicted High Tides ≥ 4.0 meters	Highest Predicted Water Level (in meters)
Sept. 14 - 20, 1989	4.6
Oct. 13 - 19, 1989	4.8
Oct. 29 - Nov. 1, 1989	4.1
Nov. 10 - 17, 1989	4.9
Nov. 27 - 30, 1989	4.2
Dec. 9 - 16, 1989	4.7
Dec. 27 - 30, 1989	4.2
Jan. 7 - 13, 1990	4.5
Jan. 26 - 28, 1990	4.2
Feb. 7 - 10, 1990	4.2
Feb. 24 - March 3, 1990	4.3
March 26 - 31, 1990	4.5
April 24 - 29, 1990	4.6
May 25 - 28, 1990	4.6
June 19 - 26, 1990	4.5

At the Sleepy Bay site (AP-13W), breaker heights exceeded 1 m on 12 different occasions between Nov. 11, 1989 and April 12, 1990. Seven of these events were related to storms between Nov. 24, 1989 and Jan. 10, 1990. The large breakers at Sleepy Bay (Figure F-1, on page F-4) on Dec. 12 coincided with a major storm (Table E-1, on page E-3) and spring high tides of 4.4 m (Photographs F-3a and F-3b, on page F-12). The Jan. 10 storm (Table E-2, on page E-3) coincided with predicted high tidal elevations of 4.2 m (Photographs F-2a, b and c, on page F-11). Significant changes were recorded on this beach during these storms, as illustrated in the accompanying photographs, and storms that coincided with high spring tides clearly were capable of reworking the backshore storm berms.

In contrast to Sleepy Bay, the data from northeast Smith Island (AP-1) show that higher breaker heights were concentrated from Dec. 30, 1989 through Feb. 6, 1990 (Figure F-2, on page F-5). The only storm event with breakers greater than 1 m that coincided with spring tides occurred Jan. 8-9, 1990. The difference in observed breaker height data between these two

exposed sites is a function of location within the Sound and the local character of the fetch area. Although winds measured at Seal Island were strongest in the first half of the winter, the shift in the prevailing direction of storm winds from the east toward the north after December caused a decrease in overall wave-energy levels at Sleepy Bay and an increase at northeast Smith Island.

At the sheltered Foul Pass location (AP-4), the average breaker heights exceeded 0.5 m on three occasions (Nov. 22; Dec. 2; and Jan. 11). For a considerable portion of the observation period, wave heights were less than 0.25 m (Figure F-3, on page F-6).

The Chenega Island site presents an example of a further reduction in shoreline wave-energy levels because breaker heights did not reach 0.5 m, exceeded 0.25 m on only one occasion, and were observed to be 0.25 m on five occasions (Figure F-4, on page F-7).

Although there are some long gaps in the time-lapse record for the very sheltered Bay of Isles site (Figure F-5, on page F-8), this location is an example of shoreline processes at the very lowest end of the wave-energy spectrum. No wave heights greater than 0.25 m were observed throughout the observation period.

The summary of the breaker heights over the observation periods (Table F-2) illustrates the difference in wave-energy levels between the five study sites, which are located on Figure F-6, on page F-9.

Table F-2
Summary Of Breaker Height Observations/Days of Estimated Breaker Heights

	Height (meters)						Total Days
	>1.00	0.50 -1.00	0.25 -0.50	<0.25	Calm	No Data	
Northeast Smith Island (AP-1)	11	26	76	38	2	0	153
Sleepy Bay (AP-13W)	12	20	78	43	0	0	153
Foul Pass, Ingot Island (AP-4)	0	3	21	49	81	0	154
Chenega Island	0	0	6	58	87	2	153
Bay of Isles	0	0	0	31	52	48	131

Figure F-1

Estimated Breaker Heights for AP-13W, Sleepy Bay/Time Lapse Video Survey (11/11/89 - 4/12/90)

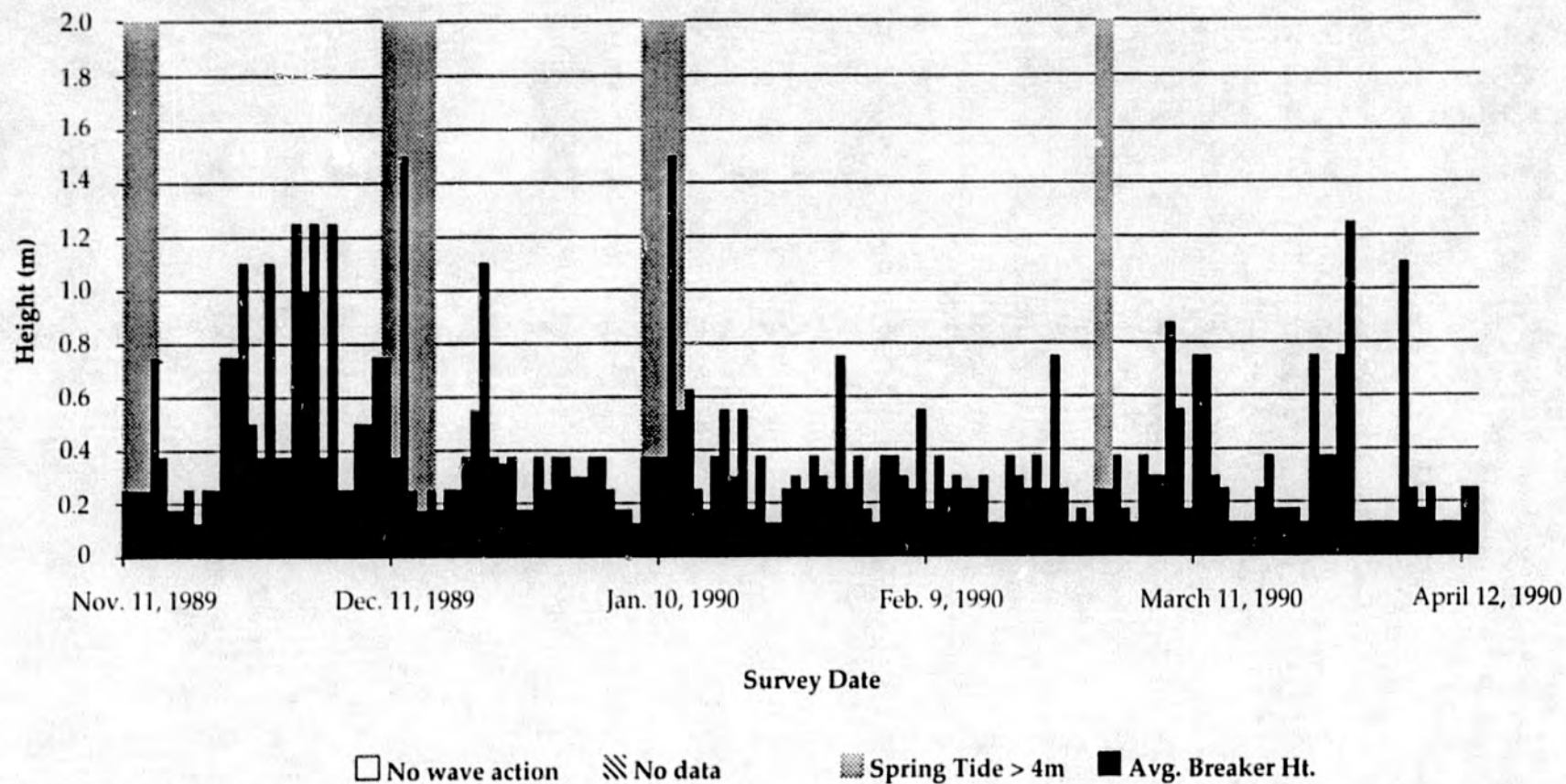


Figure F-2

Estimated Breaker Heights for AP-1, Northeast Smith Island/Time Lapse Video Survey (11/12/89 - 4/11/90)

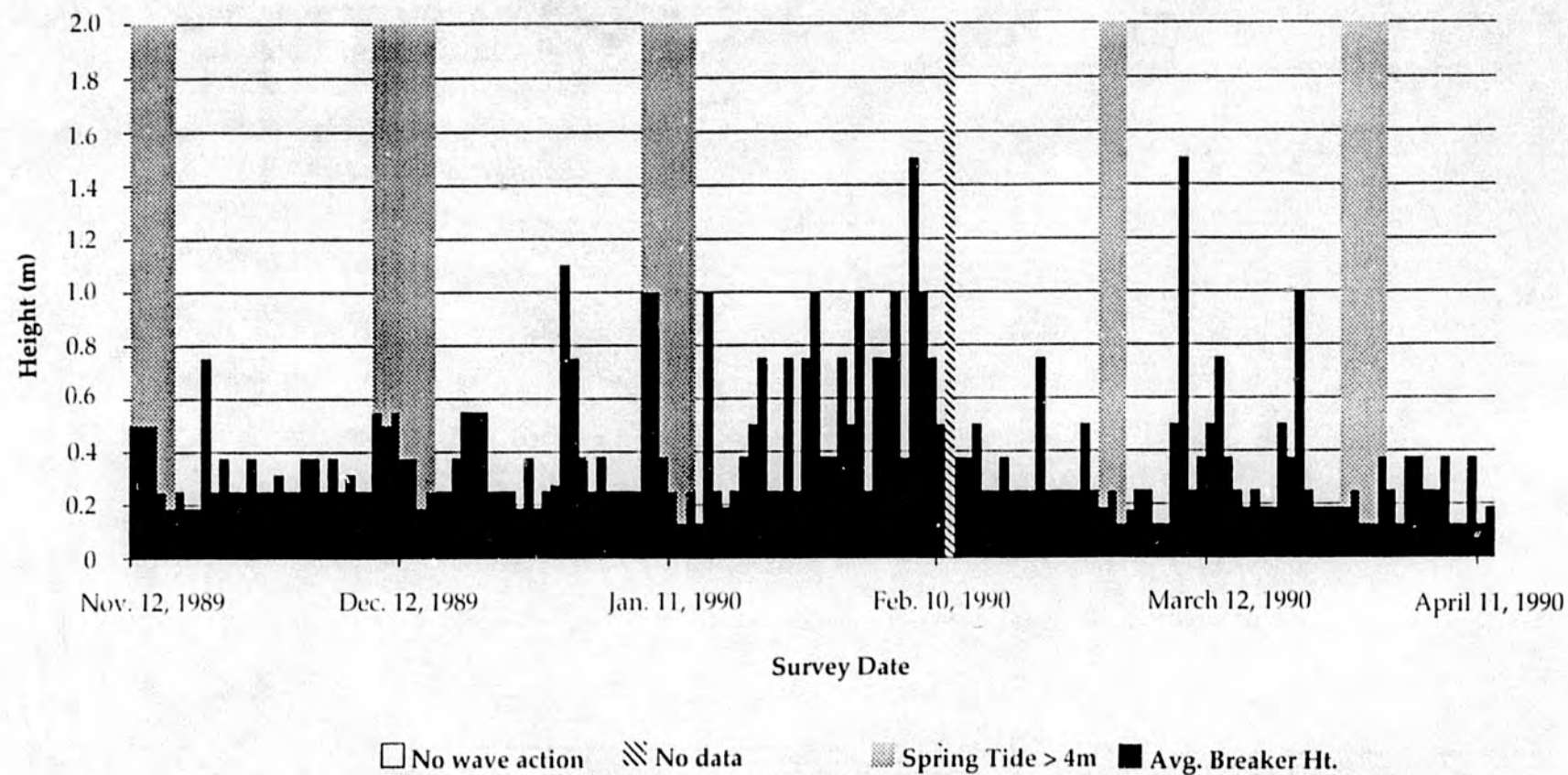
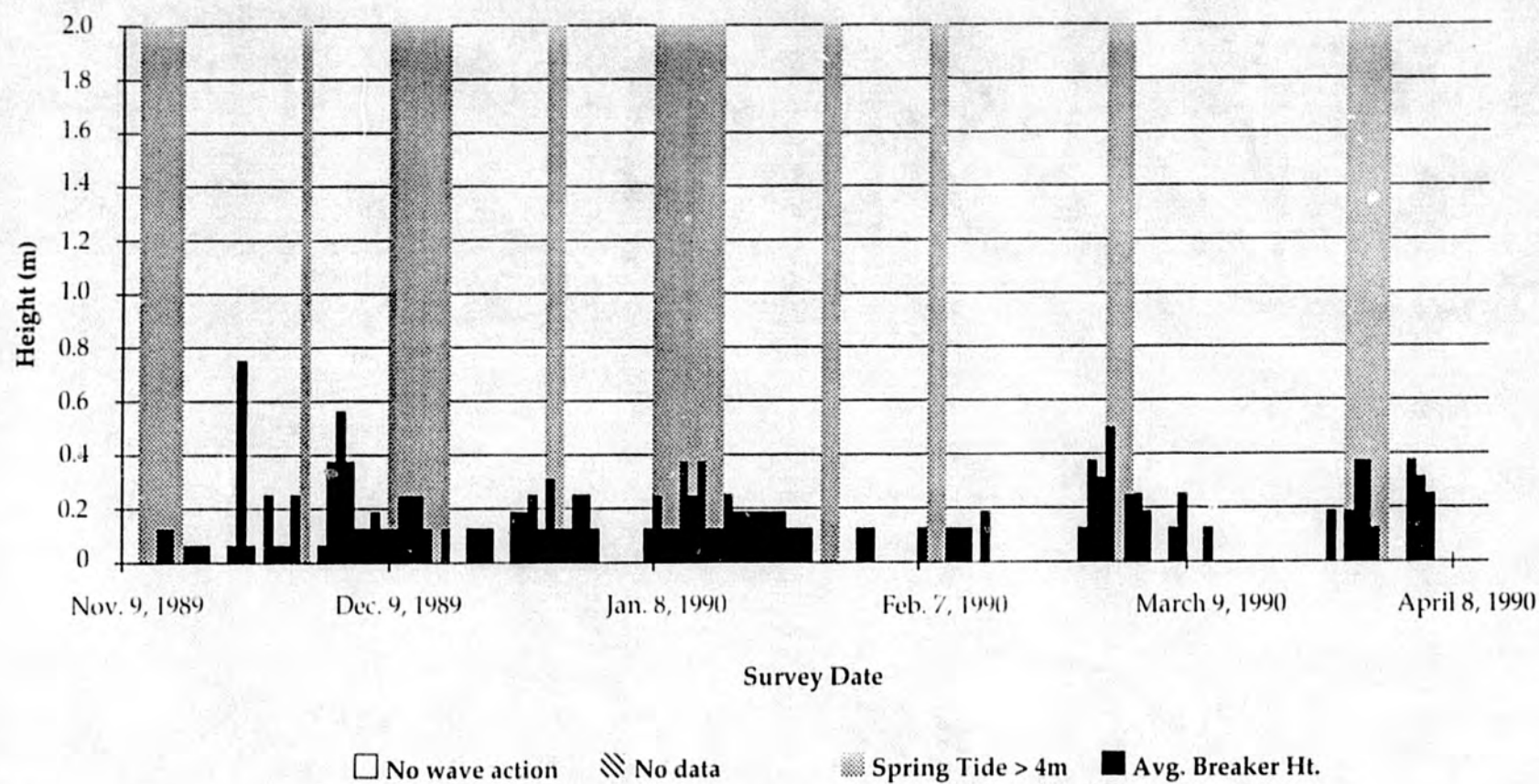


Figure F-3

Estimated Breaker Heights for AP-4, Foul Pass, Ingot Island/Time Lapse Video Survey (11/9/89 - 4/8/90)



Estimated Breaker Heights for Chenega Island/Time Lapse Video Survey (12/10/89 - 5/9/90)



Figure F-5

Estimated Breaker Heights for Bay of Isles (Short Arm)/Time Lapse Video Survey (12/4/89 - 4/3/90)

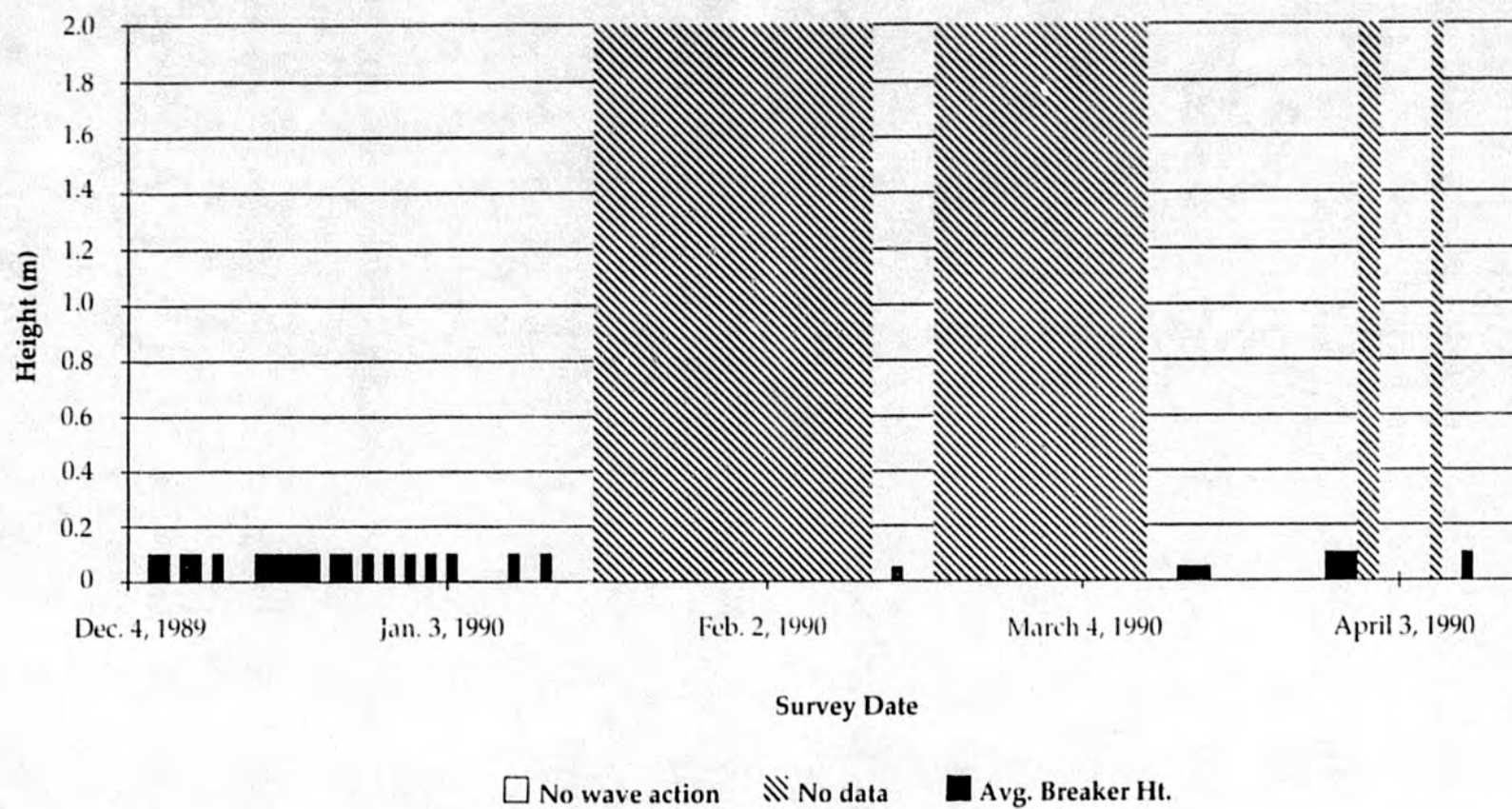
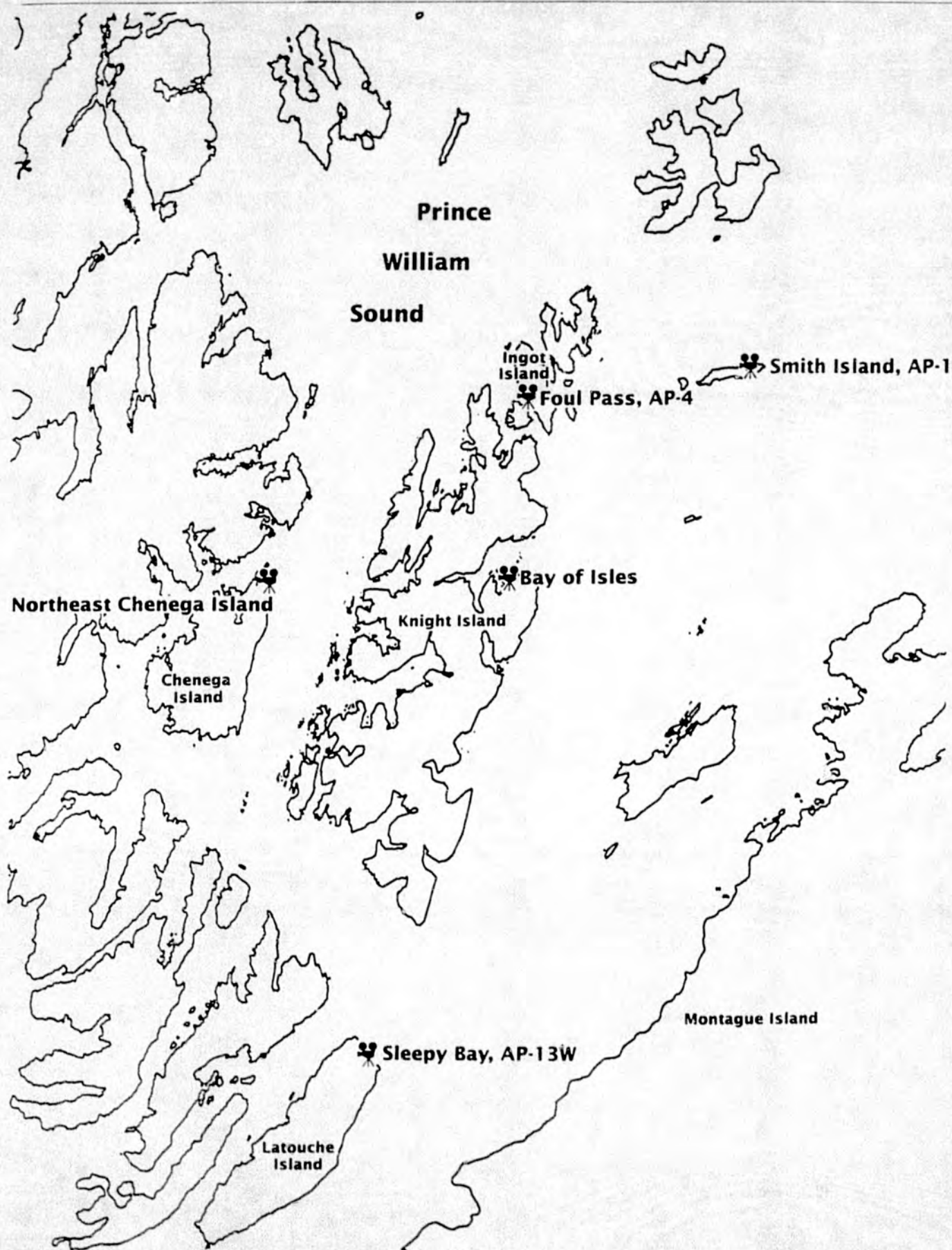


Figure F-6
Time-Lapse Camera Site Locations in Prince William Sound



F-1– Tides and breakers (0.5 meter high) produced a steep beach face with a well-sorted pebble berm ridge at site AP-13W in Sleepy Bay (Nov. 14, 1989). All photographs in this section were taken at the same site.



F-1

F-2a– A sequence of three photographs taken on the same day illustrates the tremendous energy of storm waves available to rework a beach. This photograph shows a 2-meter-high plunging breaker (Jan. 10, 1990).



F-2a

F-2b– Spring tides, combined with a storm surge and wave action, reworked backshore sediment and drift debris (Jan. 10, 1990).



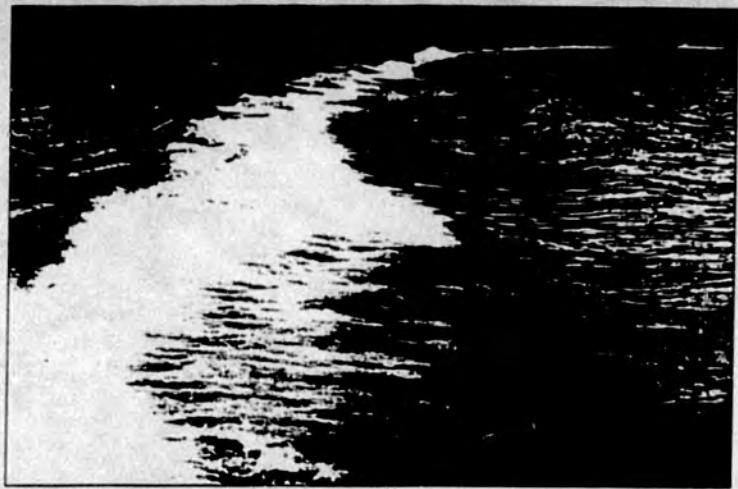
F-2b

F-2c– As the tide ebbed, drift debris and sediments were redistributed across the beachface (Jan. 10, 1990).



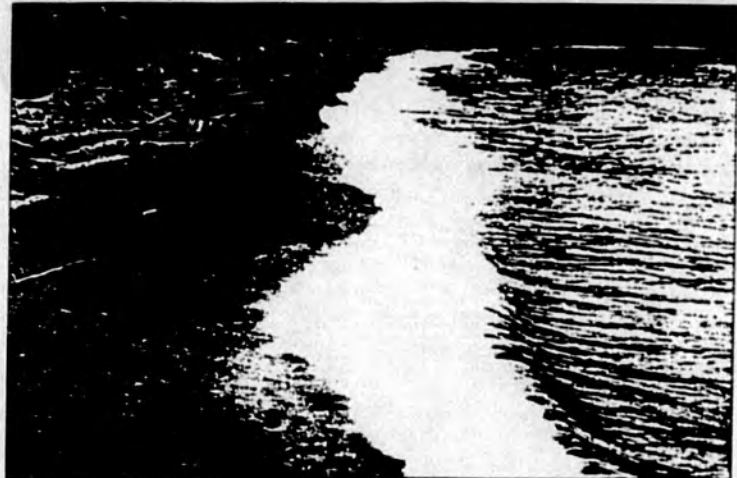
F-2c

F-3a- Wave action during spring tides is capable of reaching the backshore, reworking the highest portions of the beach (Dec. 12, 1989).



F-3a

F-3b- A 1-meter-high plunging breaker reworked the upper beachface (Dec. 12, 1989).



F-3b

F-4- The beachface was built outward with the change from erosive to constructive wave energy of late winter. The breaker forming at the shoreline was typical during late winter. Deer appeared in a number of photographs taken during middle and late winter (Feb. 26, 1990).



F-4

F-5- Constructive wave action continued to build up the beachface. The presence of several swash ridges indicated continual reworking and redistribution of beach sediments (March 21, 1990).



F-5

APPENDIX G

Summary of Biological Results

The intertidal ecology monitoring program focused on a selected core group of species, including acorn barnacles, blue mussels, limpets, littorinid snails, rockweed, and green algae. Because of their abundance the species were selected to represent key trophic groups common to this region. A permanent cross-shore transect was sampled regularly at each of 26 monitoring sites since September 1989. In February-April 1990, the program was expanded to include six non-oiled reference sites to provide information on natural patterns of recruitment, distribution and abundance. In June and September 1990, an additional 16 sites were examined. Gradual expansion of the program to 48 sites increased the range of typical habitats and oiling conditions to better evaluate the status of intertidal communities in the region.

In the summary, diagrams of the results (Figures G-1 through G-7, on the following pages) are arrayed according to the wave-energy environment, with sheltered sites to the left (AP-4, AP-6, AP-18, AH-2 and AK-1), followed by moderately exposed energy sites (AP-16 and AK-3), and with exposed sites to the right (AP-1, AP-2, AP-8, AP-10 and AP-12).

Summary of Biological Results

The rocky intertidal zones of the region support a modest diversity of marine plants and animals that interact directly and indirectly to form complex communities that vary greatly in response to the harsh environmental conditions. As a result of biological and environmental variability, a mosaic of intertidal communities in different stages of development can be found on similar shoreline types at any time within the region.

Key Organisms

A core group of organisms generally characterizes the rocky intertidal communities of the region. These plants and animals are relatively conspicuous and occur over a wide range of shoreline types and wave-energy exposures. The principal feature of the supratidal zone, which is above most wave action but receives sea spray, is a band of black lichen, which is often confused with stranded oil by untrained observers. The upper intertidal zone is often barren or is sparsely populated by a few species that are more common lower on the shore. The mid- and low-intertidal zones are characterized by acorn barnacles, littorinid snails, limpets, and rockweed (a brown algae). These organisms may be replaced, in part, by blue mussels or by a variety of brown, green, and red algae. The lower tidal zones are also variably populated by larger animals, including grazers (chitons), scavengers (crabs), and predators (anemones, whelks, starfish, sculpins, and gunnels). In addition, numerous small and inconspicuous species are present in the intertidal communities.

Zonation

The most obvious feature of intertidal communities on the rocky shores of the region is the pattern of zonation that characterizes the distributions of all organisms. Upper limits of species distributions are set by the tolerance of each organism to physical conditions, such as temperature, no ultraviolet light, and wave energy; whereas, lower limits of distributions are set by biological interactions, including competition for space and predation. Thus, zonation results from the heavy mortality of larvae or juveniles that settled too high in the intertidal zone and were desiccated, or settled too low and were eaten; those organisms that remain, therefore, occur in bands within which physical and biological conditions are more suitable for sustained growth.

Intertidal Habitats

The species and abundance of intertidal organisms likely to be found on a section of coast depend primarily on the shoreline type, and character and mobility of the sediments. Exposed beaches consisting of smaller sediments rarely support a well-developed intertidal community

because the sedentary organisms are frequently scoured from the substrate by waves and mobile sediments. The only organisms that can survive are those that can burrow rapidly and deeply in sands, or that can scuttle through small spaces between pebbles or cobbles. On exposed bedrock or boulder shores, the substrate is stable, but the organisms must be able to hold on to the rock to withstand pounding by breaking waves. Intertidal communities are sometimes well-developed on moderately exposed to sheltered shores, where the sediments are less commonly disturbed by waves.

Life Histories

The intertidal organisms of this cold temperate region have developed life history strategies that maximize growth and reproductive potential. The high nutrient content of coastal waters and longer days during the warmer spring and summer months enable species to rapidly replenish populations devastated by winter storms and freezing temperatures. These life history strategies may involve the production of very large numbers of small eggs that are broadcast into the water where they hatch into planktonic larvae and are dispersed along the coast to recolonize available intertidal shores. Species with this type of reproductive pattern are least susceptible to an oil spill because of the vast numbers of eggs and larvae produced and their wide dispersal in the plankton. Other organisms produce a fewer number of large, yolk-filled eggs, so the young hatch at an advanced stage of development with improved chances of survival; the eggs are attached to sheltered surfaces of lower intertidal sediments and are brooded by a parent in some species. Species with this reproductive pattern could be more susceptible to stranded oil but fortunately in this instance oil was rarely deposited in the lower intertidal zone.

Variability

Random mortality of intertidal organisms because of predation or battering by logs, or mass mortality resulting from regionwide freezing temperatures, commonly results in the local removal of organisms from rock surfaces. These bare patches are rapidly colonized by bacteria, algal spores and invertebrate larvae, which are present in the plankton at the time. They compete for available space and initiate the process of marine community succession. The organisms that eventually come to dominate the space may be different from those there previously because they were able to recruit to the area first or were able to displace the initial occupants. As a result of temporal and spatial variation or mortality and recolonization, similar intertidal shores are populated by a mosaic of communities in various stages of development.

Field Studies

Stranded oil adversely affected intertidal biota on most monitored sites. In assessing the extent of effect, as well as the recovery of organisms from the spill, it is important to note that on the majority of sites oil was stranded on the upper half of the intertidal zone, where the diversity and abundance of organisms is typically lower.

Furthermore, this portion of the shore is more frequently exposed by tides, so organisms in this habitat are more susceptible to daily, seasonal and annual environmental extremes, resulting in great variation in their numbers and distribution. Thus, differences in the distributions and abundances of organisms between oiled and non-oiled reference sites were small and difficult to detect unless a particular organism was especially sensitive to oil pollution or a beach was very heavily and persistently oiled.

The upper limit of distribution and average abundance of key intertidal organisms on oiled study sites surveyed in September 1989 and 1990 are compared in Figures G-1 to G-7, on pages G-7 to G-13, to illustrate the extent of recovery that occurred during the year. The graphs also compare these biological characteristics of the oiled sites and non-oiled reference sites in September 1990 as a basis for assessing the extent of recovery to normal conditions. Since oil was usually stranded on the upper shores, a temporary reduction in the upper limit of biological distributions may have occurred. Persistent oiling and treatment efforts may also have had a more pervasive effect on organisms; this effect may be reflected in reduced average abundances on a site. The upper limits of distribution are in meters above mean low water. Limited time available for surveys of each site necessitated using simple observational methods to score abundances of key organisms that were often too numerous to count within 1-meter-wide transects that extended the width of a beach. Littorinid snails and limpets were scored on a geometric scale from 0 (absent) to 10 (more than 6,000 per m²). Rockweed (*Fucus*) abundance was scored as percent cover of the sediments. Cover of barnacles and mussels was scored from 0 to 10 on a normal scale of distribution.

Discussion of Results

Because oil was stranded only on the upper shore of the great majority of beaches, reduction in the upper limit of distribution of key organisms might have been expected. However, comparison of survey results on the same site between September 1989 and September 1990 reveals that the upper limit of distribution for juvenile and adult barnacles, mussels, rockweed, and littorinid snails was very similar on most study sites. The species distributions also were comparable with those observed on non-oiled reference sites in September 1990. Barnacle spat commonly settle higher on the shore than the larval or juvenile life stages of other key organisms; on the majority of study sites, spat settled somewhat lower on

shore in September 1990 than they had the previous September. Comparison of spat distributions on oiled and non-oiled sites in September 1990 revealed no consistent tendency for spat to have settled higher on the shores of control sites (Figure G-1, on page G-7).

Limpets appear to have been the most adversely affected of the key organisms. On the vast majority of the sites surveyed in September 1989, limpets were not observed or were present in very low abundance (Figure G-6, on page G-12). During spring 1990, limpets migrated up the shore and juveniles recruited, so by September 1990 populations on most oiled sites were similar in distribution and abundance to those of non-oiled sites. However, there remained a few sites where limpets were not as abundant.

The abundances of the ubiquitous littorinid snails and juvenile and adult barnacles on the majority of oiled sites were generally comparable with, if not greater than, those of non-oiled sites by September 1990. The abundances of littorinids at this time were almost uniformly higher on oiled sites than they had been the previous September (Figure G-7, on page G-13). With few exceptions, abundance was similar to or higher on oiled sites when compared with non-oiled sites in September 1990. Similarly, the older life stages of barnacles on oiled sites were usually more abundant in September 1990 than they were at the outset of this study. With the exception of a few sites that were heavily and persistently oiled, barnacle abundances on oiled sites in September 1990 were comparable with those of non-oiled sites (Figure G-2, on page G-8).

Although mussel distribution on oiled sites exhibited little change during the period of investigation, their average abundance had increased on most sites by September 1990 (Figure G-3, on page G-9). On the remaining sites, abundance was usually low and had not changed much since September 1989. One of the Foul Passage sites (AP-4; transect 5) stands out as an exception because mussel abundance was consistently high from September 1989 through June 1990, and then declined about 60 percent by September 1990. Large amounts of crushed mussel shells were observed at this time, indicating that foot traffic had possibly resulted in significant mussel mortality. Predatory whelks were abundant on this beach and had killed great numbers of mussels, as evident from intact shells with drill holes, but predation was not responsible for the magnitude of the observed decline in mussels. For example, the abundant mussel population on the set-aside site in East Herring Bay was also plagued by dense whelks but had increased nearly six-fold by September 1990.

Rockweed was a conspicuous component of the intertidal communities of most sheltered beaches but was generally much less abundant and ephemeral on exposed sites (Figure G-4, on page G-10). The upper limit of distribution of juvenile and adult plants was usually comparable in the

two September surveys or had declined somewhat by September 1990. Average abundance of these plants on oiled sites was, for the most part, comparable in 1989 and 1990, although abundances on some of the higher energy sites had increased considerably. One exception occurred in east Herring Bay (AP-6) where average abundance had declined 18 percent by September 1990 because of the loss of most plants in one quadrat during the summer. Even so, the distribution and abundance of *Fucus* on this and other sheltered oiled sites were comparable to or greater than these on a non-oiled reference site in September 1990; on exposed beaches, the results of such comparisons were more variable.

Recruits are usually not very abundant in healthy, dense *Fucus* beds because older plants occupy and shade most suitable substrate. Thus, it is not surprising that the abundance of recruits was usually greater on sheltered oiled sites in September 1989 than during the next September (Figure G-5, on page G-11). This was probably a result of increased availability of space when the canopy of mature plants was reduced by oiling and cleanup activity. This effect was still in evidence on sheltered oiled beaches in September 1990 when recruit abundances were usually much higher than on the non-oiled reference site. The abundances of rockweed recruits on exposed sites were much more variable; recruitment often occurs on these sites, but survival is low (as evident from the low abundance of older plants) because of wave scour of the sediments.

Conclusions

Overall, the abundances and distribution of key organisms on most oiled sites in September 1990 usually were not substantially different from those observed on non-oiled reference sites. Nevertheless, the intertidal biota on a few oiled sites had apparently not completely recovered in that time. These sites had been very heavily oiled over much of the intertidal zone and had not received extensive cleanup in summer 1989. The northwest Smith Island site (AP-2) is an example; the upper limit of distribution and abundance of nearly all key organisms declined during the year, so they were restricted to the lower intertidal zone, which is below 0.4 m above mean low water (MLW). These types of sites received extensive treatment in summer 1990, and thus by summer 1991, it is anticipated that the intertidal biota on virtually all study sites will have recovered to such an extent that the communities will be indistinguishable from those on non-oiled shores in the region.

Figure G-1a

Barnacle Spat Comparisons/

Between September 1989 and September 1990 on Selected Oiled Sites

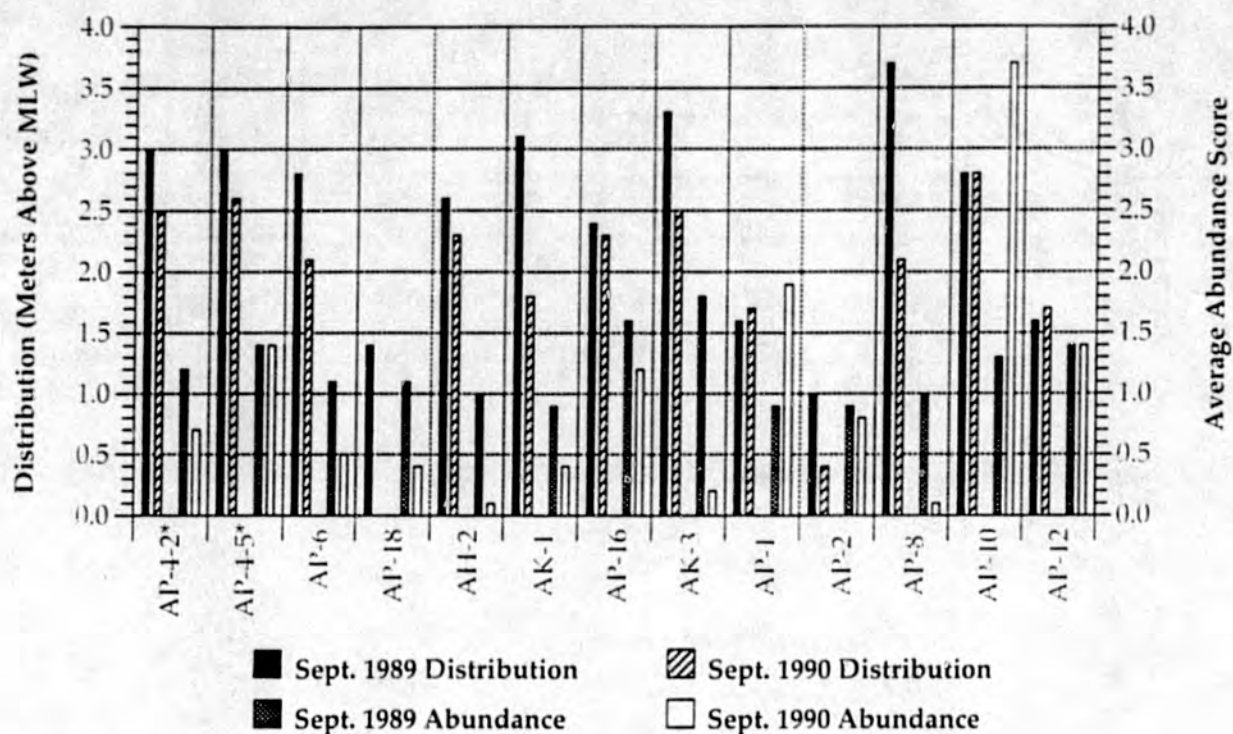
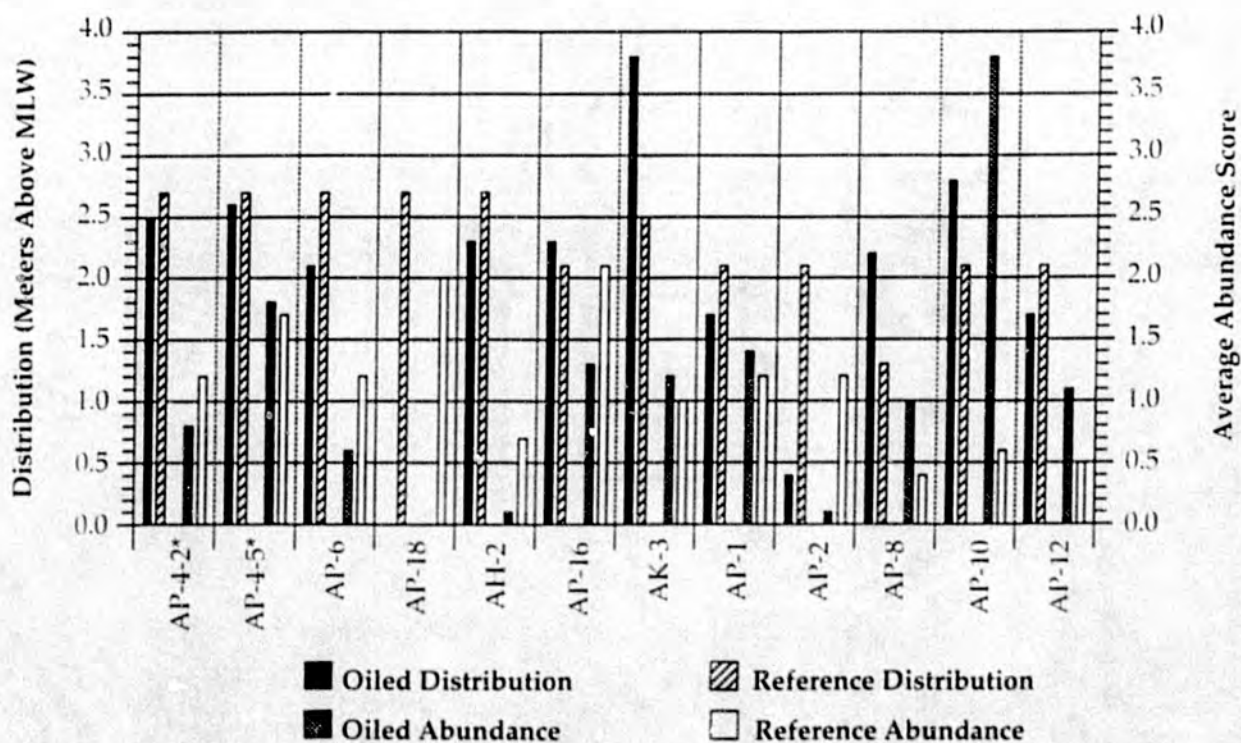


Figure G-1b

Barnacle Spat Comparisons/

Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

Figure G-2a
Juvenile and Adult Barnacle Comparisons/
 Between September 1989 and September 1990 on Selected Oiled Sites

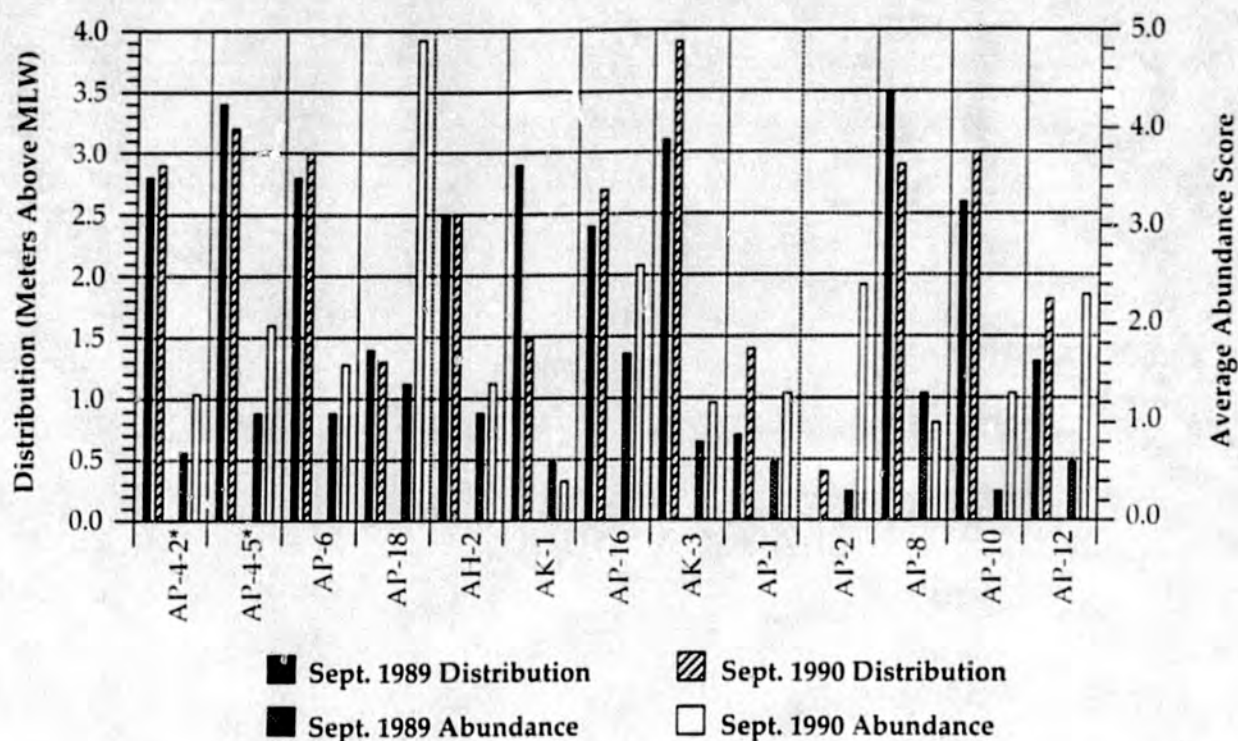
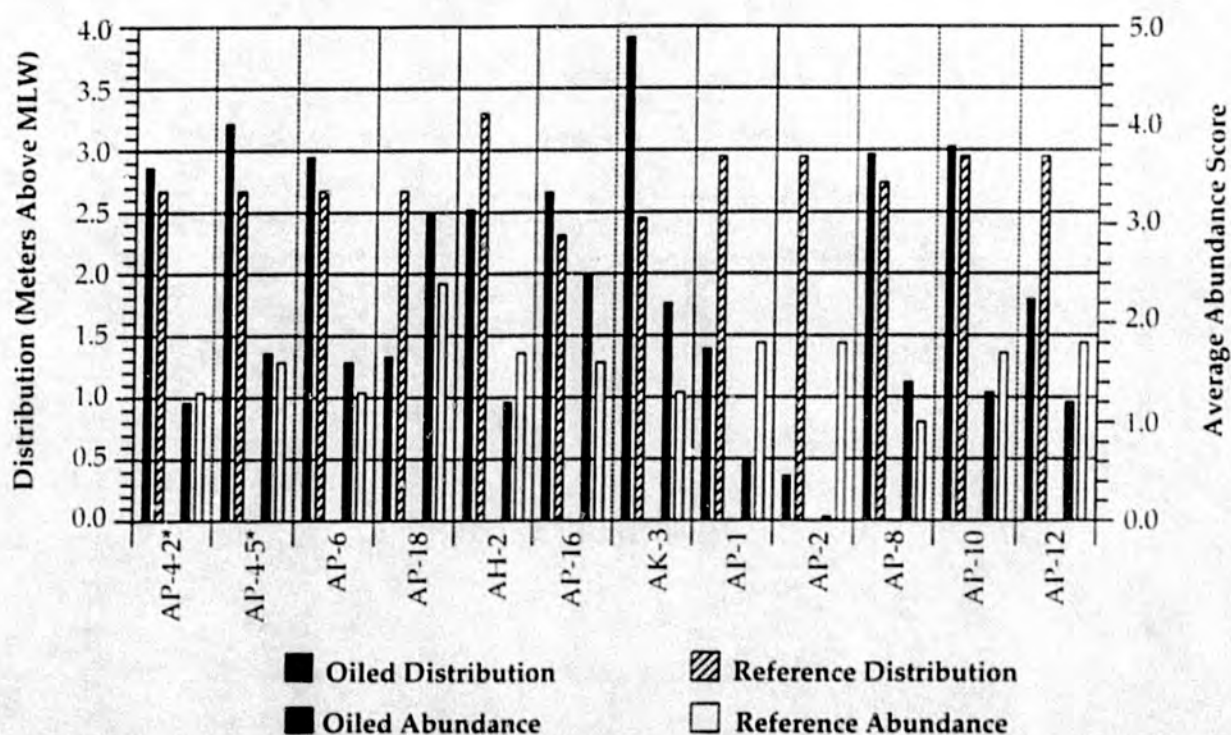


Figure G-2b
Juvenile and Adult Barnacle Comparisons/
 Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

Figure G-3a

Mussel Comparisons/

Between September 1989 and September 1990 on Selected Oiled Sites

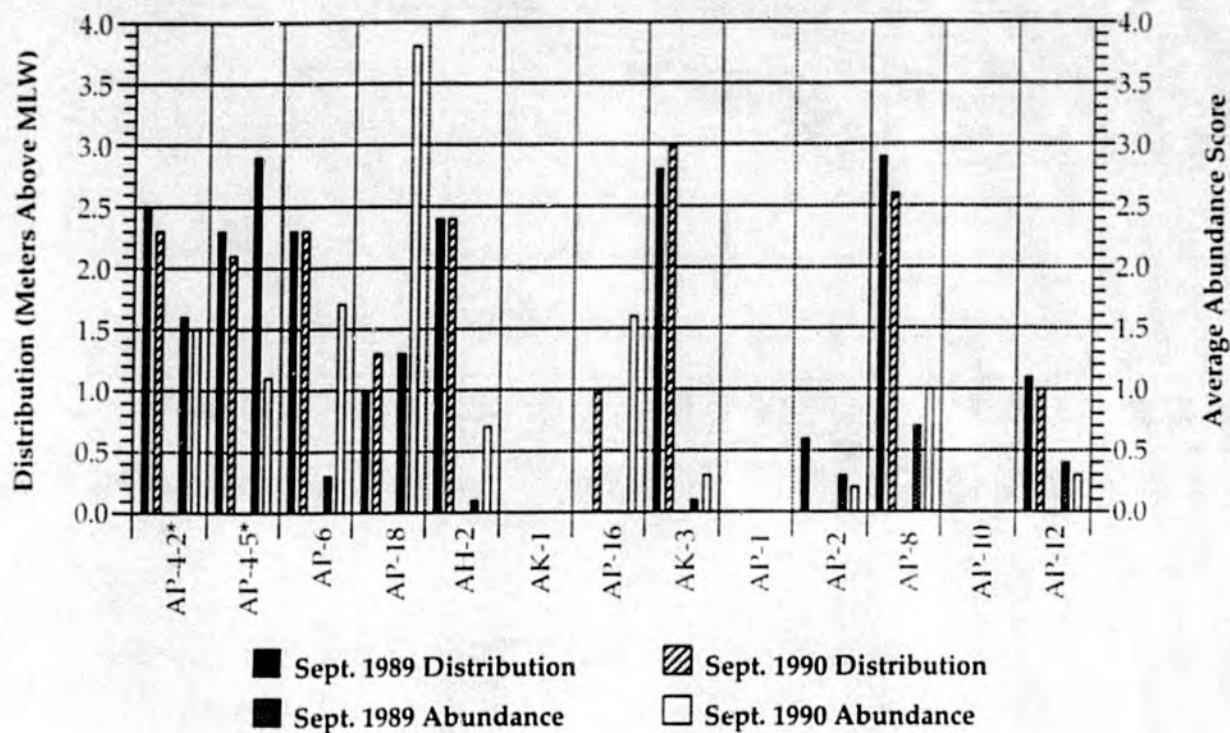
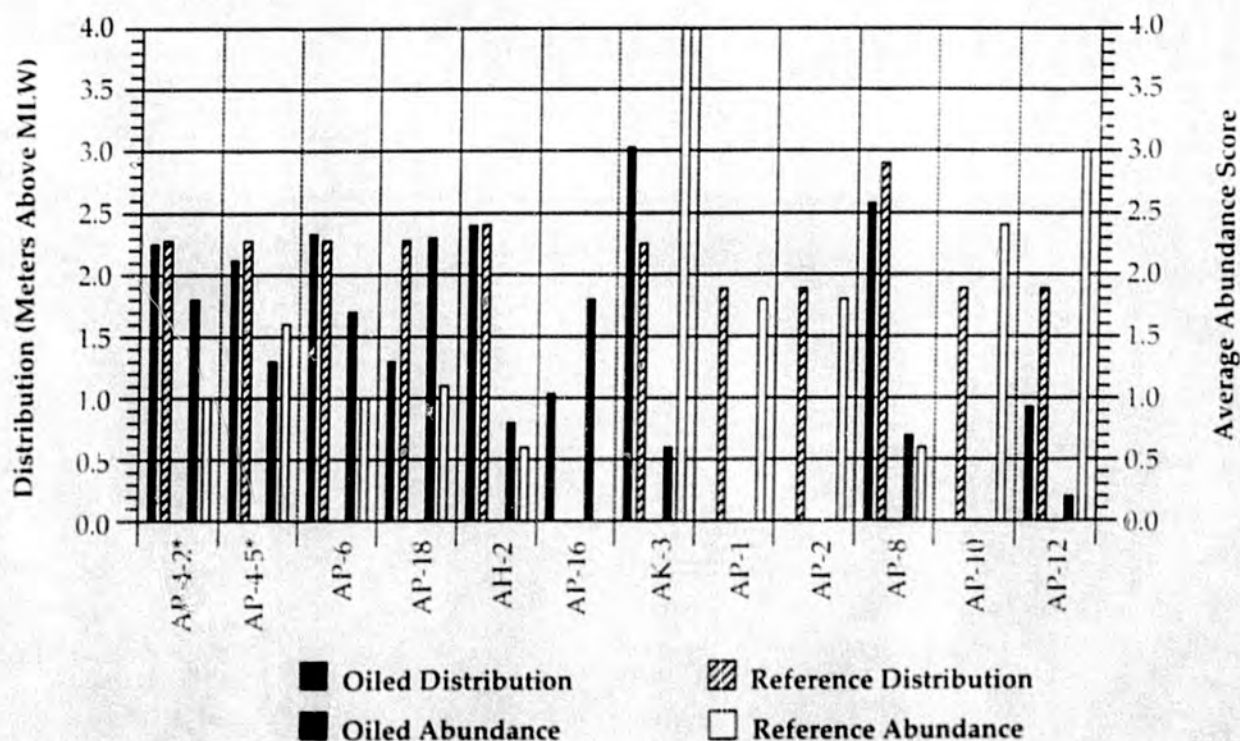


Figure G-3b

Mussel Comparisons/

Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

Figure G-3
Juv

**Comparisons/
September 1989 and September 1990 on Selected Oiled Sites**

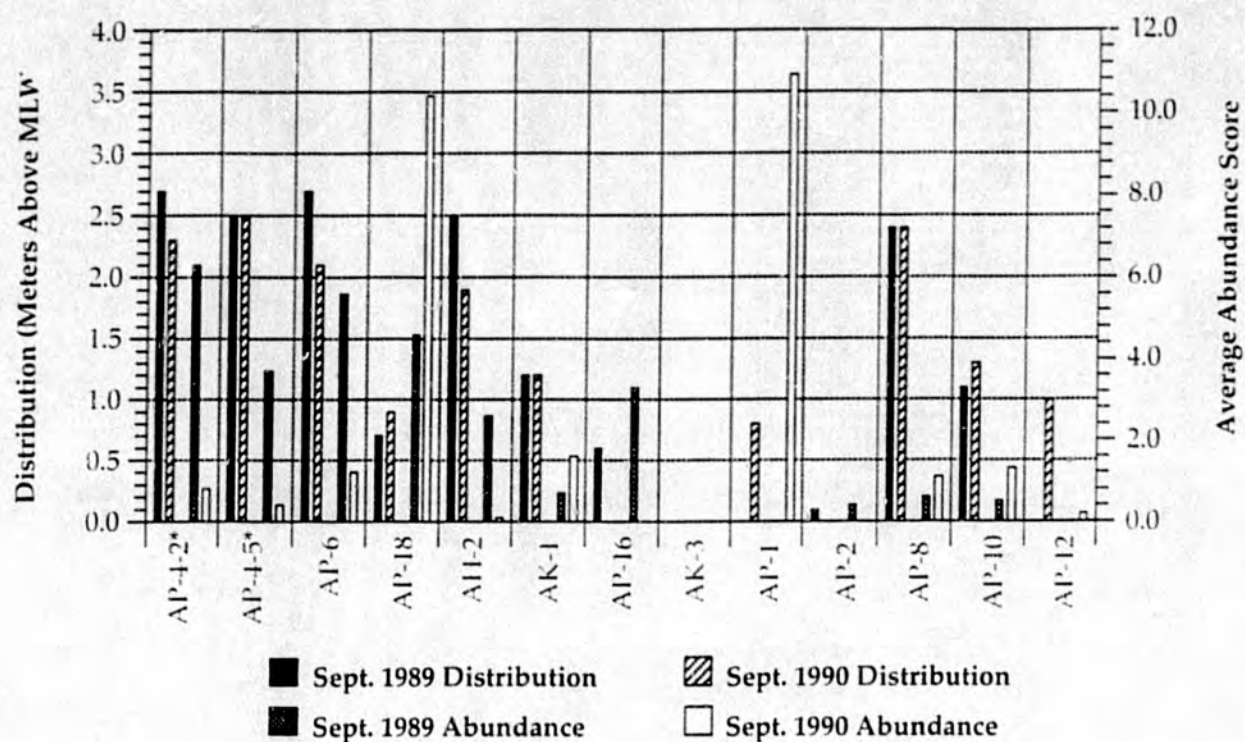
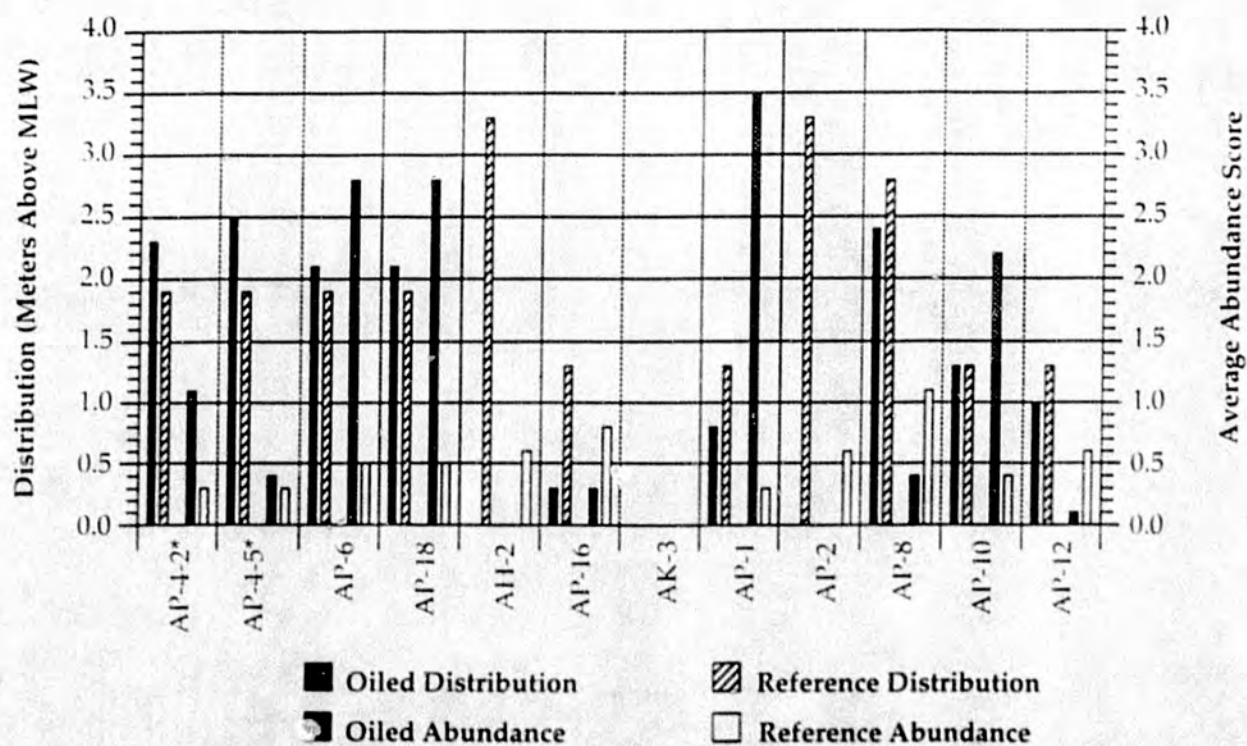


Figure G-4b
Fucus Recruit Comparisons/
Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

Figure G-5a

Juvenile and Adult Fucus Comparisons/

Between September 1989 and September 1990 on Selected Oiled Sites

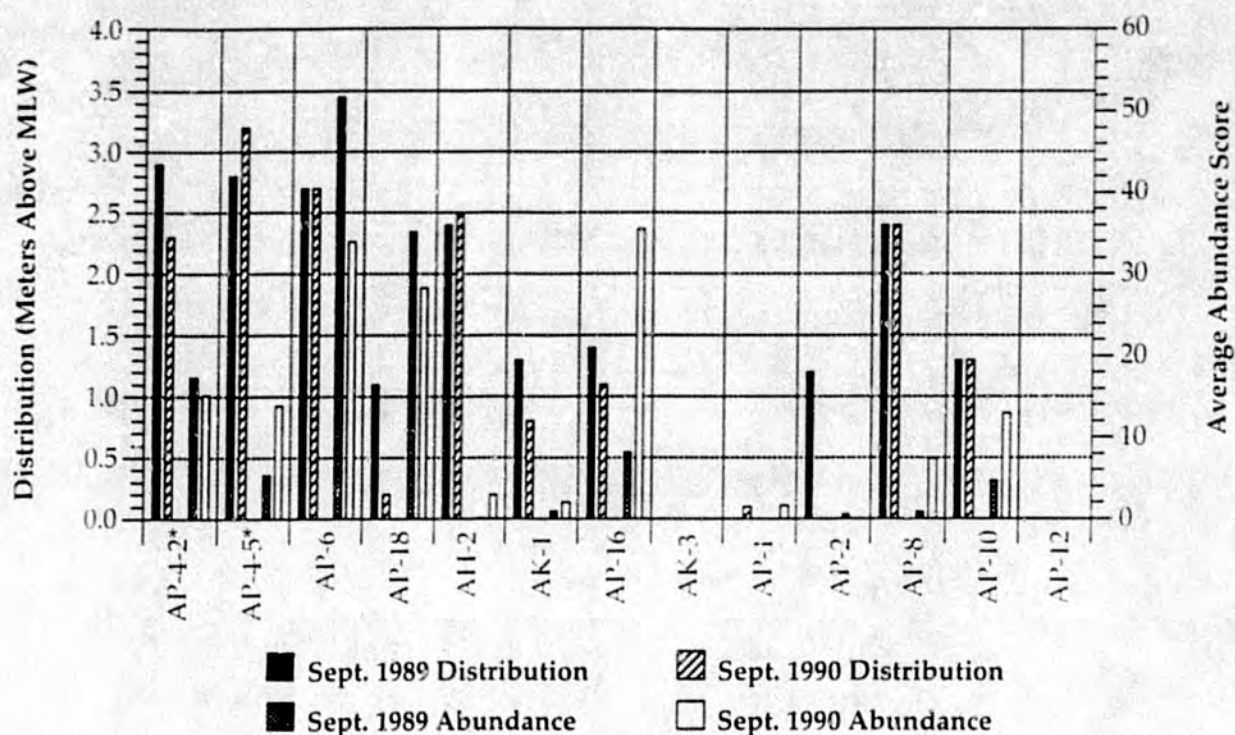
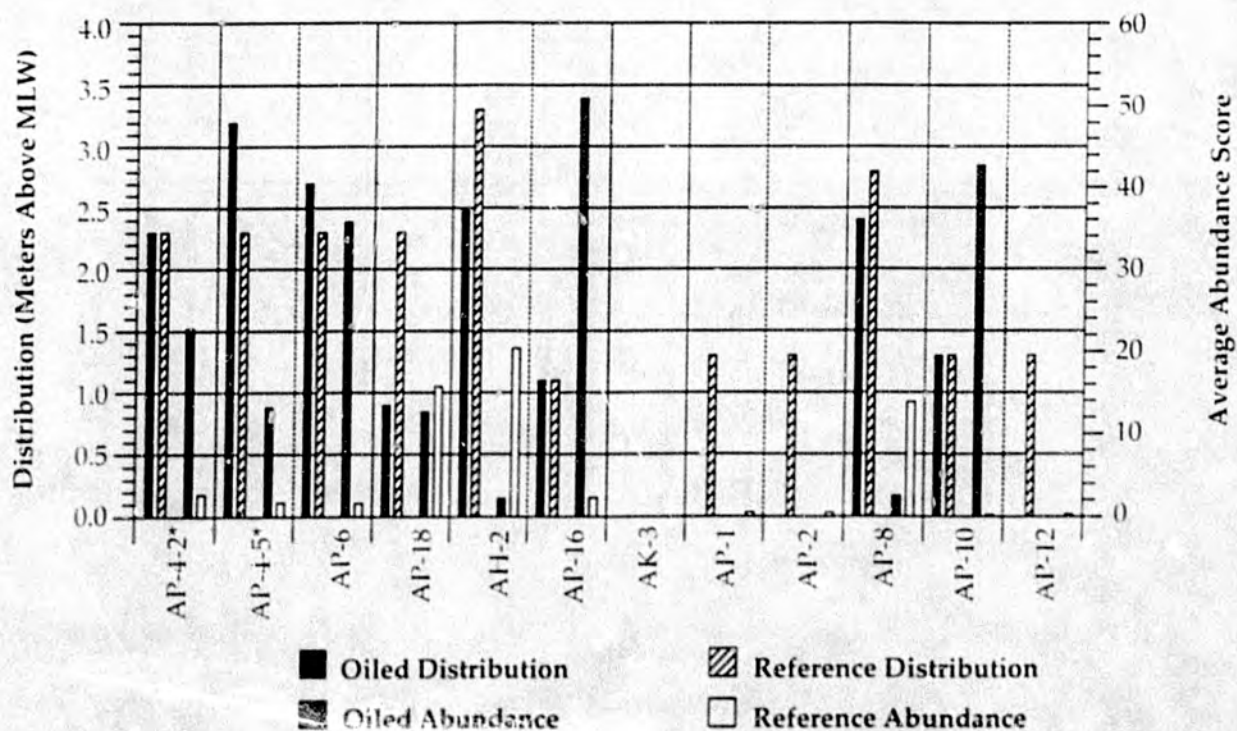


Figure G-5b

Juvenile and Adult Fucus Comparisons/

Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number

Figure G-6a

Limpet Comparisons/

Between September 1989 and September 1990 on Selected Oiled Sites

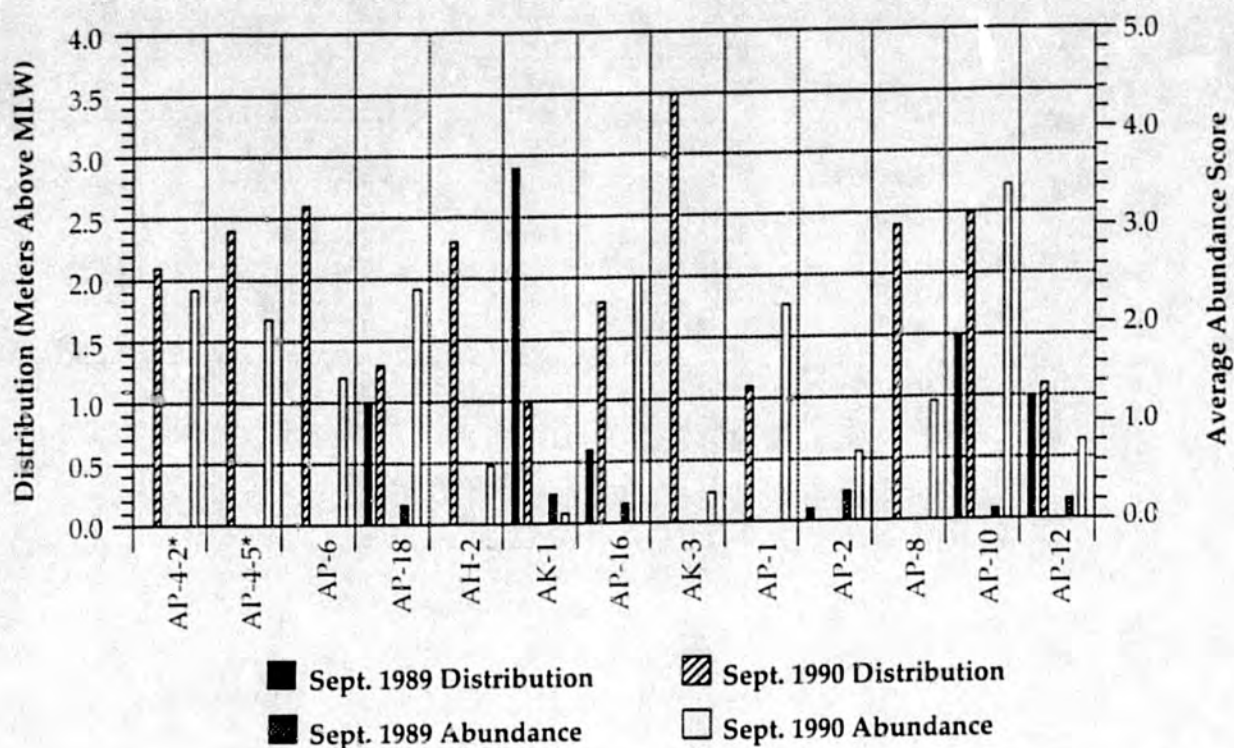
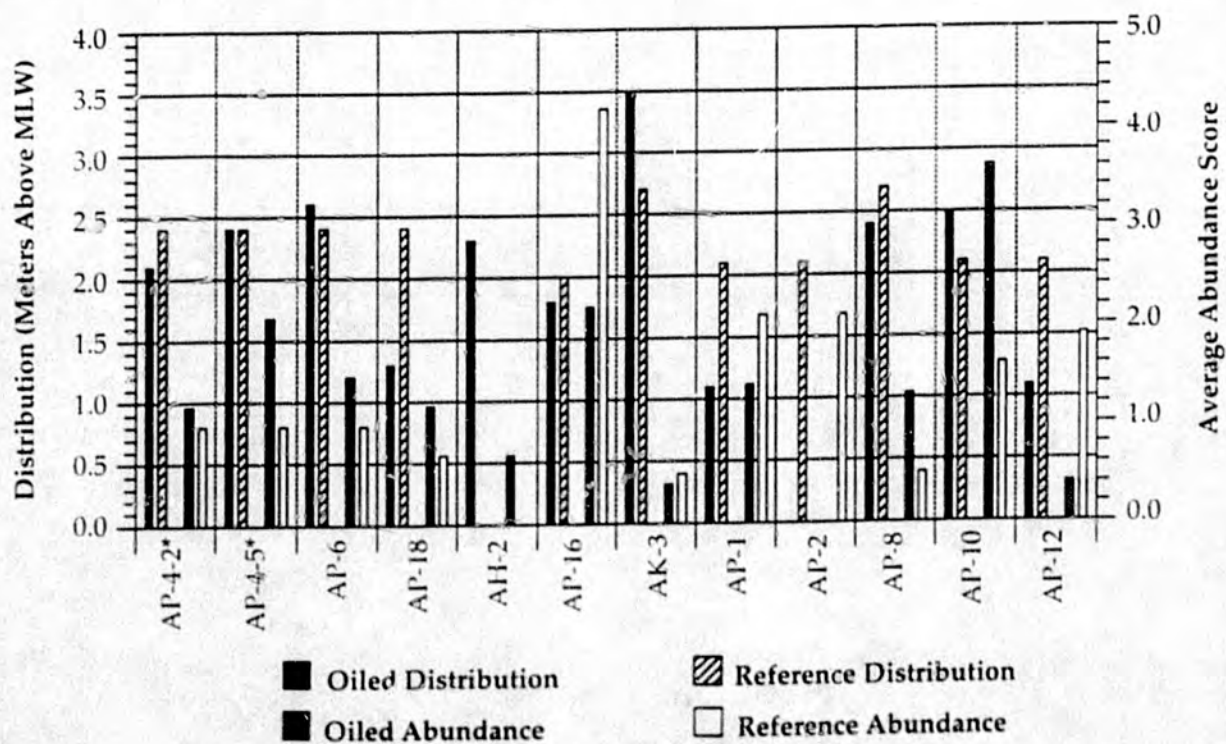


Figure G-6b

Limpet Comparisons/

Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

Figure G-7a
Littorinid Snail Comparisons/
 Between September 1989 and September 1990 on Selected Oiled Sites

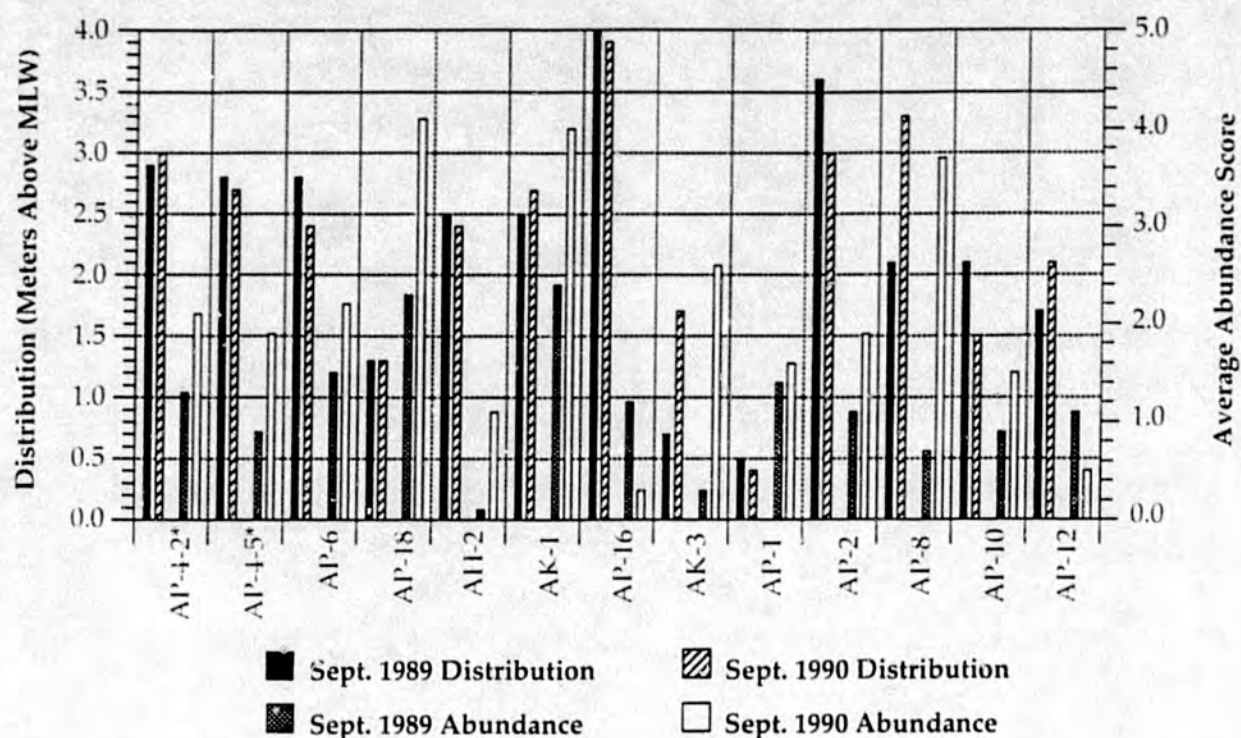
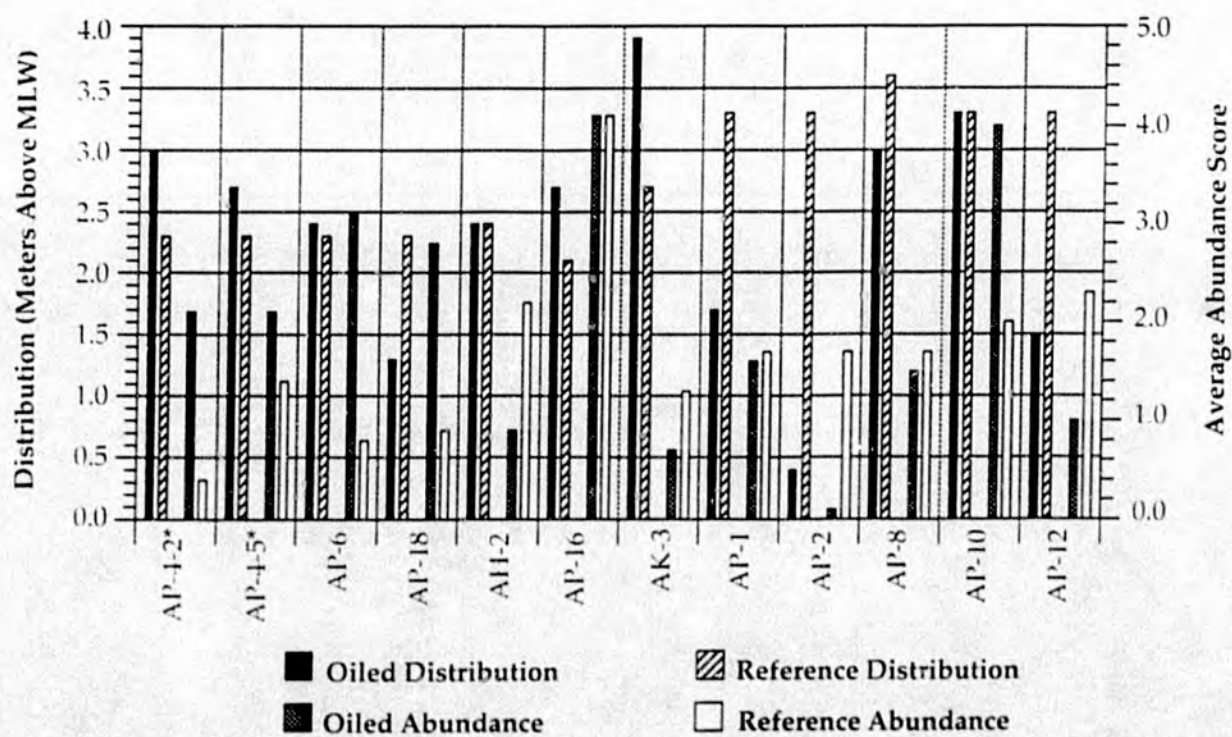


Figure G-7b
Littorinid Snail Comparisons/
 Between Oiled and Non-Oiled Reference Sites in September 1990



*Last number at AP-4 refers to transect number.

WOODWARD- CLYDE

About the Firm

Woodward-Clyde is an international consulting firm that has achieved prominence in environmental, geotechnical, and waste management services. Founded in 1950, the firm has grown to more than 50 offices and over 2,000 employees worldwide. *Engineering News-Record* has listed the firm as one of the top 50 U.S. design firms since that listing began in 1965.

Woodward-Clyde, with headquarters in Denver, is recognized internationally as a leader in the field of oil spill cleanup and research. Staff members have accumulated practical experience through participation in or observation of more than 100 oil spills worldwide.

Woodward-Clyde's professional experience in the marine and coastal environments has been brought together in its Coastal Science and Engineering Center to provide an interactive approach to biological, chemical, and physical studies. The center provides a forum for professional staff to bring state-of-the-art technology and innovative solutions to problems. The scientists and engineers of the center have considerable international as well as Alaskan experience.

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This report should be referenced as follows: Owens, E.H., 1991. "Changes in Shoreline Oiling Conditions 1-1/2 Years After the 1989 Prince William Sound Spill." Unpublished report. Woodward-Clyde, Seattle. Washington. 52 pages and appendixes.

Assessing the Risk to Pacific Herring from Offshore Gas and
Oil Development in the Southeastern Bering Sea

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ABSTRACT

The U.S. Department of the Interior (USDOI) began the presale process for conducting an offshore gas and oil lease sale in the southeastern Bering Sea (North Aleutian Basin) during 1973. Due in part to potential environmental effects from gas and oil operations, an offshore gas and oil lease sale--Sale 92, North Aleutian Basin--was not held in this area until October 1988. As a result of this sale, 23 leases were issued for gas and oil exploration. The USDOI's Minerals Management Service (MMS) has spent approximately \$235 million to gather information needed to identify resources potentially at risk from offshore gas and oil exploration and development. The MMS is continuing to support studies concerning these resources and is focusing on species of specific concern near areas currently under lease.

During the prelease process for Sale 92, concern was expressed about the potential effects of gas and oil activities on Pacific salmon (all five species), Pacific herring (*Clupea harengus pallasi*), and king crab (*Paralithodes camtschatica*).

Gas and oil activities or accidents that have the greatest potential for affecting these species are chronic or acute discharges of pollutants, such as oil and associated fluids. Studies conducted for MMS and others indicate that early life stages of these species are vulnerable to spilled oil and other pollutants. The "Window of Maximum Vulnerability" (WMV) is considered to be that period when the early life stages are most sensitive to pollutants, e.g., spilled oil. Studies results show that the WMV for Pacific herring in the southeast Bering Sea falls between May and July, when early life stages are found in shallow coastal waters. A numerical simulation conducted for MMS by the National Marine Fisheries Service and a synthesis report (Thorsteinson, 1984) evaluating the potential effects of spilled oil on offshore fisheries resources indicated that even during the WMV, gas and oil activities pose minimal threat to offshore fisheries resources. This report also concluded that an offshore oil spill poses a minimal threat to herring stocks spawning in Port Moller, Alaska. The findings are consistent with findings that the Exxon Valdez oil spill had no measurable effect on herring eggs and larvae in Prince William Sound, Alaska.

INTRODUCTION

The U.S. Department of the Interior (USDOI), Minerals Management Service (MMS), began leasing submerged lands on the Outer Continental Shelf (OCS) off Alaska for gas and oil exploration in April 1976 with OCS Lease Sale 39 in the northeastern Gulf of Alaska. Since then, MMS has conducted 14 OCS lease sales and leased 3.2 million hectares, and industry has drilled some 67 exploration wells in Federal waters offshore Alaska. Oil in economically producible quantities has been found under State waters in Cook Inlet and under Federal and State waters in the Beaufort Sea--some 6 wells as of May 1990 have been classified as producible in the Federal OCS portion of the Beaufort Sea near Prudhoe Bay.

MMS began preparing for an gas and oil leasing program in the southeastern Bering Sea in 1974, with the first lease sale (Sale 51) scheduled for October 1977 (USDOI, MMS, 1985a). After several delays and sale cancellations, 23 leases from Sale 92 were let in 1988 (Fig. 1). Exploration of these tracts has been suspended pending court review (USDOI, MMS, 1990a).

In addition to recognizing legal mandates guiding the Department's activities, Departmental managers are aware that the harvest of marine resources--primarily fish (Pacific salmon, Pacific herring, and walleye pollock) and crab (king and Tanner crabs)--plays an important part in cultural and commercial activities within Alaska. They, therefore, have directed considerable resources to assessing potential conflicts between traditional uses of these resources and the exploration for gas and oil resources.

In 1973, MMS initiated the Environmental Studies Program (ESP) to support the OCS oil- and gas-leasing program off Alaska. The purpose of the ESP is to develop information needed to assess and mitigate potential effects that proposed gas and oil leasing and development might have on the human, marine, and nearshore environments. Since its inception, the ESP has conducted some 521 environmental studies in Alaska at a cost of over \$235 million (1973-1990). Over half of these studies have focused on fisheries-oceanography issues. Information

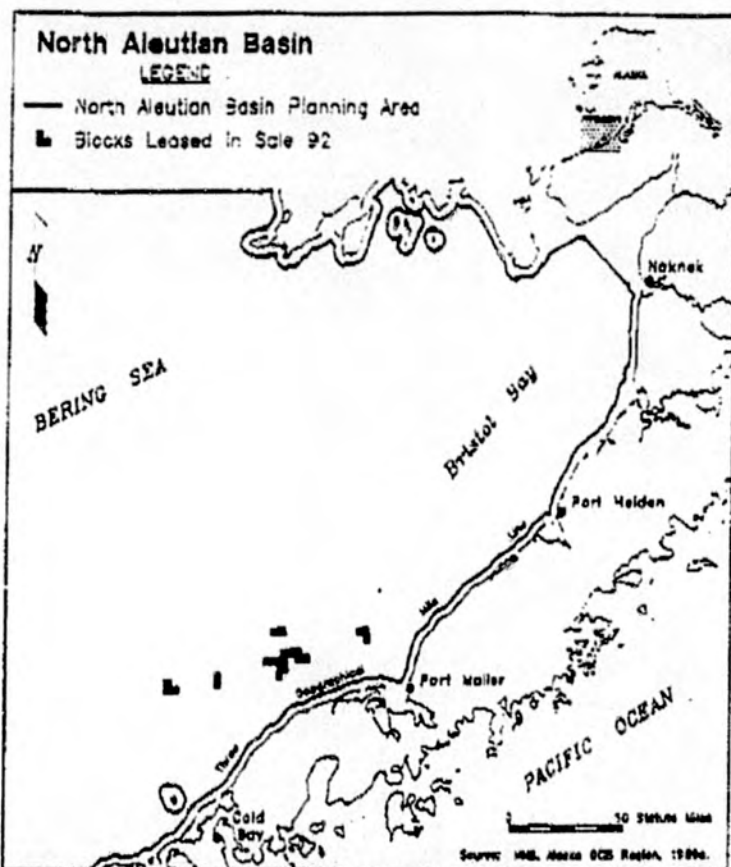


Figure 1. North Aleutian Basin Planning Area.

acquired through this program is in the forefront of subarctic and arctic research and is used to support offshore leasing and management decisions.

Fisheries resources in the Bering Sea have been exploited for well over a century, with annual harvests exceeding 1.2 million metric tons (mt) during the past decade. Walleye pollock, flounders, and Pacific cod account for the majority of this harvest. Other important fisheries include salmon, Pacific herring, and crab (king and snow). With the exception of the salmon and Pacific herring fisheries, most fisheries occur offshore, well away from the coast. The salmon and Pacific herring fisheries occur near shore and in estuaries in Bristol Bay and along the Alaska Peninsula.

In 1975, MMS funded the Alaska Department of Fish and Game (ADF&G) to conduct a resource-assessment survey of Pacific herring and other fishes spawning in coastal waters of the eastern Bering Sea (Barton, 1972) from Cape Charikof on Unimak Island to the Seward Peninsula (Barton, 1972). Annually,

ADF&G conducts areal surveys throughout the region to estimate spawning-herring biomass. In addition to the spawning surveys discussed above, MMS has supported several projects to synthesize available environmental information concerning the southeastern Bering Sea and to develop information pursuant to potential gas and oil in the region. These projects have included a synthesis of environmental information (Thorsteinson, 1984); a forage-fish workshop (USDOL, MMS, 1987); a monograph of eastern Bering Sea resources (Hood and Calder, 1981); an open-file geologic report (USDOL, MMS, 1983a); an exploration and development report (USDOL, MMS, 1985b); Environmental Impact Statements (EIS's) for gas and oil lease sales (USDOL, MMS, 1982a,b; 1983a,b; and 1985a,c,d); a study of the fish use of inshore habitats (Isakson, 1986); and an environmental characterization of the nearshore zone (LGL, 1987).

PROBLEM STATEMENT

Pacific herring, because of their general life history, are considered to be at considerable risk from spilled oil. This perceived risk was well stated by Rice et al., 1988, when they suggested that the spawning strategy of herring made them particularly vulnerable to the effects of an oil spill because spawning adults and their maturing gonads could be exposed to spilled oil, and the spawned eggs and larvae would be subjected to an oil-contaminated environment.

Background

MMS is charged with managing the exploration for and development of offshore gas and oil resources in an environmentally sound manner. To accomplish this goal, MMS evaluates the potential environmental effects of gas and oil exploration and development on marine resources. MMS has, for example, evaluated the potential effects from offshore gas and oil activities on eastern Bering Sea Pacific herring in EIS's prepared for each of the five gas and oil lease sales in the Bering Sea (USDOL, MMS, 1982a,b; 1983a,b; and 1985a,b,d). Evaluations contained in these documents were based, in part, on results from studies that simulated the potential effects of spilled oil on fisheries resources in the southeastern Bering Sea (Laevastu and Fukuhara, 1984, and Thorsteinson, 1984).

These evaluations and simulations concluded that spilled oil would have minimal or no measurable effect on offshore fisheries resources, including Pacific herring. However, because site-specific information on many of the fisheries resources in coastal waters was not available, the simulations were unable to evaluate the potential effects of an offshore oil spill on certain coastal resources, e.g., herring eggs and larvae.

Following the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska, MMS funded a study to determine the potential effects that spilled oil may have had on Pacific herring eggs and larvae. Developing eggs and larvae were collected from areas that appeared to have been heavily oiled as a result of the oil spill and compared with samples collected from areas that were not exposed to the spilled oil. Results from these studies indicate that the oil spill had no measurable effect on herring eggs and larvae in Prince William Sound in 1989 (McGurk, 1990a,b).

Status of Gas and Oil Exploration

The tracts that currently are under lease for possible gas and oil exploration are offshore of and upstream from Port Moller, Alaska. This estuary supports a large spawning stock of herring that may be at risk from an offshore oil spill.

This report provides an evaluation of the risk to the herring resources in Port Moller from an offshore oil spill and builds on information developed by numerous other authors.

PORT MOLLER--PHYSICAL ENVIRONMENT



Figure 2. The Port Moller Estuary (McGurk, 1990).

The Port Moller estuary (lat. 56° N, long. 160° 35' W.) is located on the north side of the Alaska Peninsula (Fig. 1). The largest (878 square kilometers [km²]) coastal estuary in the southeastern Bering Sea, it consists of Nelson Lagoon, Mud Bay, Herendeen Bay, and Moller Bay (Fig. 2). The estuary is shallow, 4 to 17 meters (m), and is characterized by extensive shallow mud flats drained by narrow dendritic drainage channels. Herendeen Bay, however, is deeper (> 100 m) and is connected to the remainder of the estuary by the relatively narrow and shallow (< 30 m) Johnson Channel. Tidal range within the estuary is about 3 m, and current velocities in the

channels can exceed 140 centimeters per second (cm/s).

Circulation of water into and through the Port Moller complex has been described by Greengrove, 1990, as being dominated by tidal forces and major regional storm events. During each tidal cycle, marine water tends to enter on the west of the estuary and exit on the east side, and there is a net discharge from the estuary of about 13 cm/s. Waters within the estuary tend to be well mixed; however, waters in Herendeen Bay may become stratified during periods of low winds.

Prevailing winds are from the southeast and average 8.9 knots. Summer temperatures range from 6 to 18 °C, and winter temperatures range from 6 to -20 °C (Brower, 1988). Although sea ice seldom extends as far south and west as Port Moller, the estuary freezes over each winter.

The Eastern Bering Sea is separated into three hydrographic regions--the outer shelf, the middle shelf, and the coastal region--which are separated by the shelf-break front, the middle front, and the inner front, respectively. Coastal circulation during the ice-free period generally is east along the Alaska Peninsula and to the northeast along the inner-front boundary (Fig. 3). The mean flow past Port Moller appears to be northeastward along the Alaska Peninsula with a velocity of about 2 to 5 centimeters per second (cm/s). Circulation along the coast is dominated by tidal currents (Schumacher and Kinder, 1983). Only about 3 percent of the kinetic energy within the coastal region is associated with weather events.

The Port Moller biota is dominated by large stands of eelgrass (*Zostera marina*) and rockweed (*Fucus distichus*). The area is an important staging area for water-

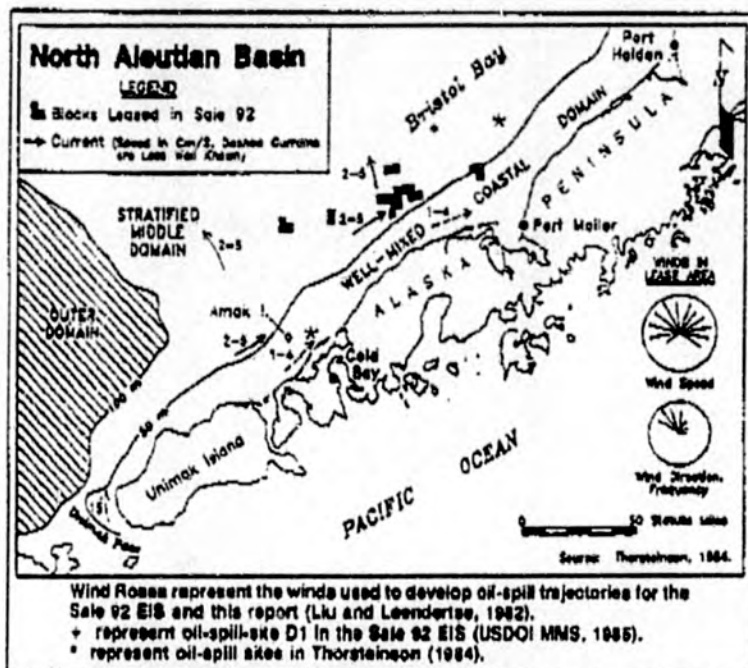


Figure 3. Prevailing coastal circulation during typical summer conditions. Redrawn from Thorsteinson (1984).

fowl and supports spawning populations of Pacific herring (*Clupea harengus pallasii*) and red and blue king crab (*Paralithodes camtschatica* and *P. platypus*, respectively).

BIOLOGICAL NOTES

Pacific herring are found throughout the eastern Bering Sea at various times of the year. Fish appear to overwinter in the central Bering Sea (Thorsteinson, 1984, and Funk, 1987) and return to coastal spawning sites in late spring-early summer (Wespestad and Barton, 1981). Figure 4 shows the relative abundance and timing of herring spawning in the eastern Bering Sea. Wespestad and Barton (1981) estimated that the eastern Bering Sea herring biomass ranges from 0.374 to 2.75 million metric tons (mt). Results from aerial surveys in 1978 indicated that the coastal spawning biomass for the eastern Bering Sea was 432 to 864 thousand mt. Laevastu (1985) used biomass estimates of 1,409 and 1,121 (kg/km²) for juvenile and adult herring, respectively, occurring in Port Moller when conducting his analysis. A recent study by McGurk (In Press) suggests that the minimum herring biomass spawning in Port Moller during the 1989 spawning period ranged from 1,784 mt (based on aerial surveys) to 1,788 to 2,241 mt (based on larval abundance).

Spawning occurs subtidally (McGurk, 1989) on marine vegetation (eelgrass and rockweed) throughout Moller and Herendeen Bays (Fig. 5) between early May and

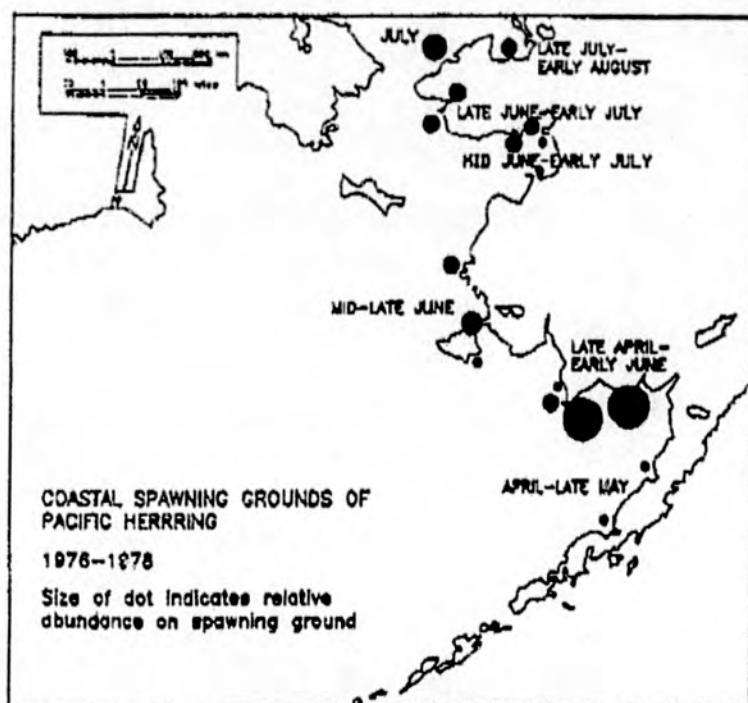


Figure 4. Distribution, spawning time, and relative abundance of Pacific herring in the eastern Bering Sea. Redrawn from Wespestad and Barton (1981).

late June. Winter-ice scour removes most of the intertidal vegetation in Port Moller. High-water turbidity within the Port Moller complex and poor weather conditions in the region make spawning surveys, both aerial and shipboard, difficult. As a result, shoals of pre- and postspawning adults are seldom seen for more than one or two tidal cycles, and clouds of milt in the water indicating active spawning are seldom observed. To date, efforts to collect developing herring eggs spawned within the estuary have not been successful (McGurk, 1990, pers. commun.). Therefore, the actual spawning beds have not been mapped, and the extent of potential spawning beds has been determined only by estimating the areal extent (using aerial photos of the area) of marine vegetation in areas where herring larvae have been collected.

Three cohorts of herring eggs hatched in Port Moller between May 10 and June 30, 1989 (McGurk, 1989). Initial observations indicate that three cohorts also hatched during the same time period in 1990 and that yolk-sac larvae that were collected in July suggested the existence of a fourth cohort (McGurk, 1990, pers. commun.); these data are currently being analyzed. Herring larvae collected in Moller Bay appear to grow faster than those collected from Herendeen Bay; this may be related to the warmer water temperatures observed in Moller Bay (Fig. 6) (McGurk, 1989).

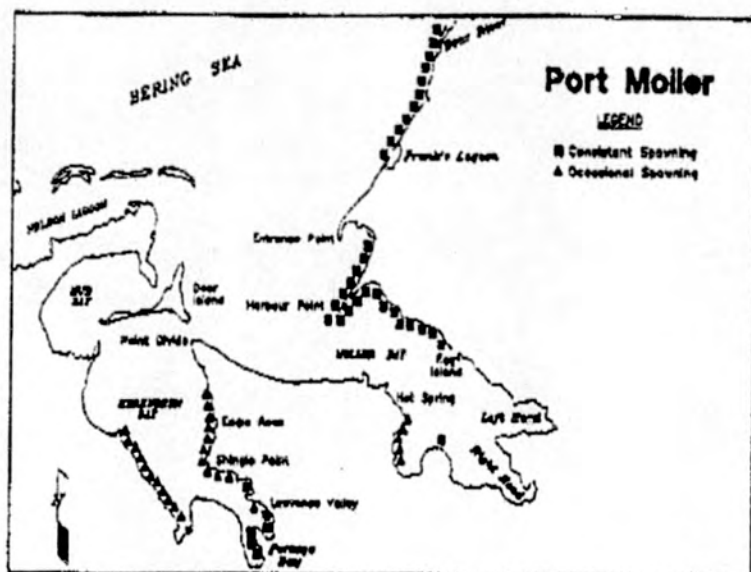


Figure 5. Distribution of herring spawning locations in Port Moller, Alaska. Redrawn from McGurk (1989).

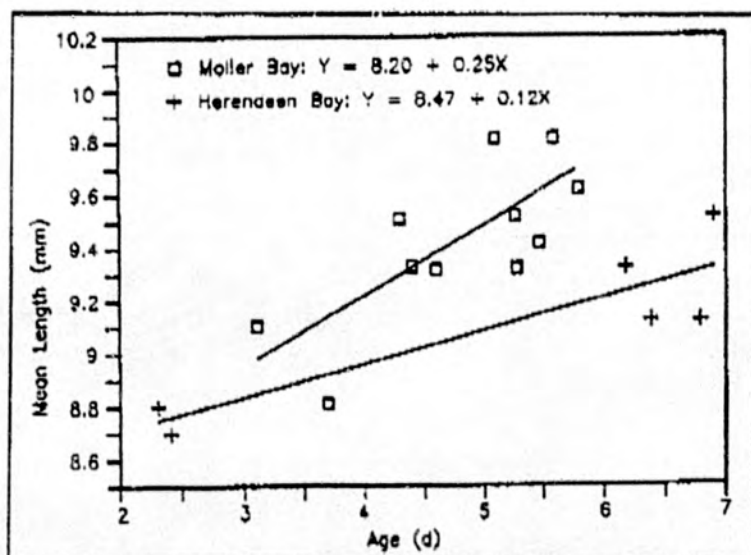


Figure 6. Growth Rates for Pacific herring larvae collected from Herendeen and Moller Bays, Port Moller, Alaska, in 1989 (McGurk, 1989).

Herring larvae undergo diurnal vertical migrations, apparently following their prey field (McGurk, 1989a). The younger larvae are found primarily in the top 15 m of the water column, whereas older, larger larvae have been found as deep as 35 m. At night, smaller larvae tend to be most abundant in the 5 m of the water column and the larger larvae in the top 25 m (McGurk, 1990, pers. commun.). Robertson, 1988, reported that herring larvae in British Columbia waters tended to be most common at depths between 5 and 10 m. The vertical distribution of larvae in the Port Moller estuary (McGurk, 1990, pers. commun.) is controlled in part by the degree of stratification or mixing within the water column. Off Harbor Point, a well-mixed area, larvae were collected throughout the water column, 0 to 25 m, whereas in Herendeen Bay—an area of limited vertical mixing—few larvae were captured below 15 m (larger larvae were found at the deeper depths). McGurk found herring larvae to be most abundant near the eelgrass beds off Right Head in Moller Bay and south of Bluff Point in Herendeen Bay. Other studies suggest that the herring will begin schooling and move out of the estuary as the season progresses, possibly by September.

RISK ASSESSMENT

The probability of an oil spill affecting a significant portion of the herring population or spawning and rearing habitat is expressed by the relationships presented in Table 1. The effects (P_{effect}) that spilled oil may have on Pacific herring resources

Table 1. Information needed to evaluate the potential effects of an oil spill on herring resources in Port Moller, Alaska.

$P_{\text{effect}} = P_{\text{threat}} \times P_{\text{transport}} \times Q_{\text{amount}} \times Q_{\text{rate}} \times T_{\text{toxicity}} \times R_{\text{resource}}$ where	
P_{threat}	$P_{\text{spill}} \times P_{\text{WMV}}$
$P_{\text{transport}}$	$T_{\text{to shore}} \times T_{\text{PM}}$
Q_{amount}	$Q_{\text{floating}} \times Q_{\text{in water column}} \times Q_{\text{in bottom sediments}}$
Q_{rate}	$C_{\text{concentration}} \times D_{\text{time}}$
T_{toxicity}	$H_{\text{downing}} = H_{\text{rearing}} \times B_{\text{biomass}}$
R_{resource}	
P_{effect}	Probability of a significant effect on herring resources and habitats in Port Moller, Alaska.
P_{threat}	Probability of an oil-spill event occurring during the window of maximum vulnerability (WMV).
P_{spill}	Probability of a spill event occurring.
P_{WMV}	Probability of a spill event occurring during the WMV.
$P_{\text{transport}}$	Probability of oil spilled on or near tracts currently under lease for oil and gas exploration being transported by winds and currents into Port Moller.
$T_{\text{to shore}}$	Probability of being transported to shore.
T_{PM}	Probability of being transported into Port Moller.
Q_{amount}	The amount of oil spilled.
Q_{rate}	The rate of spilled oil, that portion that is floating or stranded, that is dispersed and dissolved in the water column, and that is deposited in bottom sediments.
Q_{floating}	The portion of oil floating or stranded.
$Q_{\text{in water column}}$	The portion of oil dispersed and dissolved in the water column.
$Q_{\text{in bottom sediments}}$	The portion of the oil incorporated into the bottom sediments.
T_{toxicity}	The concentration of hydrocarbons and duration of exposure to the hydrocarbons needed to have a lethal or sublethal effect on herring.
$C_{\text{concentration}}$	The concentration of hydrocarbons on the surface, floating or stranded, in the water column, and in bottom sediments.
D_{time}	The duration of exposure to concentrations of hydrocarbons.
R_{resource}	The resources and habitat at risk from an oil spill.
H_{downing}	Area of potential downing habitat in the Port Moller estuary.
H_{rearing}	Area of potential rearing habitat in the Port Moller estuary.
B_{biomass}	Biomass of herring spawning within the Port Moller estuary.

in Port Moller are related to the probability of a spill occurring (P_{spill}); the joint probability that spilled oil will reach the coast and also will enter the Port Moller estuary ($P_{\text{transport}}$); the amount of oil spilled (O_{amount}); the time required for the spilled oil to reach the resource at risk (O_{time}); the toxicity (T_{toxicity}) of the oil when it reaches the resource at risk (toxicity is a function of the amount of hydrocarbons dissolved or suspended in the water column ($O_{\text{concentration}}$)); the duration of exposure to oil (O_{duration}); and the herring's sensitivity to specific hydrocarbon compounds; and the resource at risk (R_{resource}), which in this evaluation include the spawning habitat (H_{spawning}), rearing habitat (H_{rearing}), and biomass of herring spawning in Port Moller (B_{biomass}). Other possible effects, i.e., bioaccumulation, reduction of prey density, etc., are considered minor (Varanasi and Malins, 1977; Cimato, 1980; and USDOI, MMS, 1990b) and are not considered in this evaluation.

Table II. The probability of an oil-spill event occurring during the WMV.

	Probability
Oil-Spill Event	57%
Oil Spill Occurring During WMV	19%
The WMV is 3 months long (May to July)	
Source: USDOI, MMS, 1985a.	

P_{spill} (Table II). The probability (P_{spill}) of an oil-spill event occurring as a result of gas and oil leasing in the area was evaluated in the Sale 92 EIS and also in the Environmental Assessment (EA) (USDOI, MMS, 1985a and 1985b) and the North Aleutian Basin Synthesis Report (Thorsteinson, 1984). The Sale 92 EA estimated that under the offshore-loading scenario, the most likely number of 1,000 barrels (bbl) or greater oil spills occurring

is less than one; for spills greater than 100,000 bbl, the most likely number is 0. The probability of one or more spills of 1,000 and 100,000 bbl occurring is 57 percent and 7 percent, respectively.

The WMV for herring spawning in Port Moller is assumed to be 3 months, May through July, based on the time that spawning herring, spawned eggs, and larvae are most vulnerable to spilled oil. Information needed to determine the most probable season during which an oil spill is most likely to occur is not available. However, the author assumes that the probability (P_{WMV}) is related to the proportion of the year that is identified as the WMV (Table II).

Table III. Transport probability.

Probability of Spilled Oil Contacting the Coast Within 30 Days	
1,000-barrel spill	27%
100,000-barrel spill	2%
Probability of Spilled Oil Contacting Port Moller Within 30 Days	8%
Probability of Spilled Oil Contacting Coast (Port Moller) Within 4 Days	13%
Probability that Spilled Oil Will Enter Port Moller (Thorsteinson, 1984)	20%
Source: Liu and Leendertse, 1982; Thorsteinson, 1984; and USDOI, MMS, 1985a.	

$P_{\text{transport}}$ Table III indicates that the probability of a 1,000-bbl oil spill occurring and contacting the coast within 30 days is 27 percent. For a spill of over 100,000 bbl, the probability of coastal contact is 2 percent. There is a 6-percent probability of the spilled oil contacting the Port Moller area within 30 days following a 1,000-bbl spill. Figure 7 shows the simulated trajectories for an oil spill occurring at release point D-1 (near the area currently under

lease) under summer (June-August) conditions (Liu and Leendertse, 1982). These trajectories indicate that the most likely path for spilled oil will be toward the east along the Alaska Peninsula. The trajectory analysis also indicated that sustained onshore winds (13% probability) could drive the oil onshore within 100 hours.

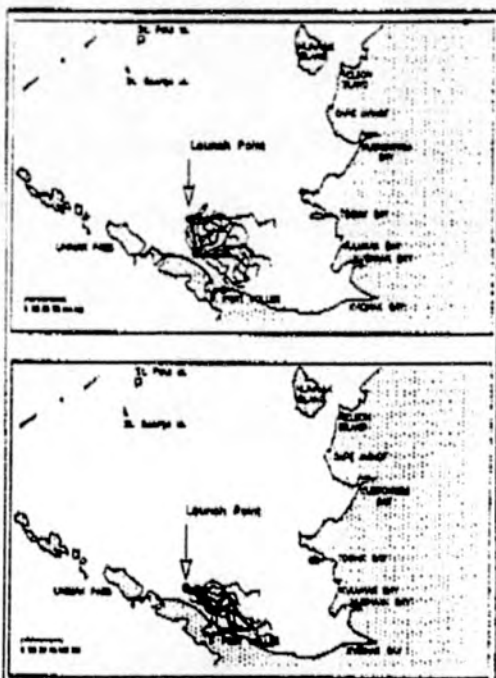


Figure 7. Simulated 30-day trajectories for oil spilled from launch points near tracts currently under lease (Liu and Leendertse, 1982). Redrawn from Thorsteinson, 1984.

Participants in the 1982 synthesis meeting chose to assume that 20 percent of the oil that reached the coast would enter Izembek Lagoon. Since similar conditions prevail off Cape Seniavin (Port Moller), they assumed similar probabilities for spilled oil reaching the coast in this area.

Oil spill. The median-size spill for OCS platforms and pipelines is 7,000 and 6,000 bbl, respectively, and 9,000 and 11,500 bbl for U.S. and Alaskan tankers, respectively (LaBelle, 1990). Using similar statistics, participants in the North Aleutian Basin Synthesis Meeting in March 1992 decided to evaluate the potential effects of a 10,000-bbl spill (2,000 bbl spilled per day for 5 days) on regional resources.

O_{rate} The rate of oil weathering is dependent on environmental

conditions, wind, air temperature, water temperature, etc., and the specific composition of the spilled oil. Figure 8 summarizes the weathering process or partitioning of spilled Prudhoe Bay crude oil under subarctic conditions. Within the first 24 hours following a spill, 11 percent of the oil--mostly the volatile, highly toxic compounds--will have evaporated; 4 percent will have dispersed into the water column as small droplets; 1 percent will have dissolved; and the remainder, 84 percent, will be present on the surface as a slick or water-in-oil mousse. By the fourth day following the spill, only some 70 percent of the oil will remain on the surface (Thorsteinson, 1984). Under prevailing June wind conditions, the spilled oil will not persist as a contiguous slick but will form streaks or windrows, thereby increasing the area covered by the spilled oil (a 10,000-bbl spill may cover about 18 km²).

By the 10th day following a spill, approximately 55 percent of the oil will remain on the surface as floating or stranded oil (O_{floating}). Once floating oil reaches the coast, it tends to be blown and washed ashore, where some will be incorporated into the beach sediments and the remainder will be remobilized during high tides and storm events. Twenty eight percent of the oil will be dispersed or dissolved in the water column ($O_{\text{in water column}}$), and a small fraction (1%) of the oil will have become incorporated in bottom sediments ($O_{\text{in bottom sediments}}$).

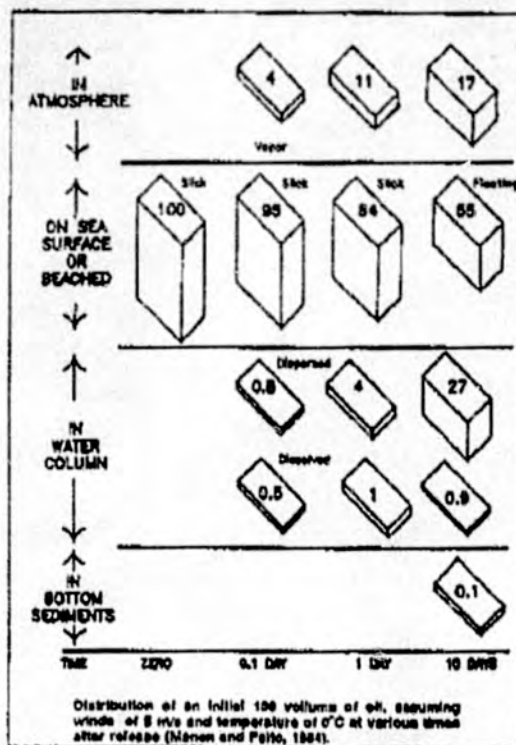


Figure 8. Speculative mass balance for Prudhoe Bay crude oil (USDOL, MMS, 1985a).

The Sale 92 EIS (USDOL, MMS, 1985a) reported that lethal effects on larvae and eggs were observed at concentrations of 0.1 to 1.0 ppm and that sublethal effects were observed at 0.01 to 1.0 ppm (Table IV).

Results from oil-effects studies are difficult to compare because of the differing experimental and analytical methods employed (Neff, 1990). More contemporary studies are exposing organisms to the water-soluble fraction (WSF) of crude oil (only a small fraction of the crude oil is soluble). The parameters used by Neff, 1990, are similar to WSF parameters used by other authors.

Rice et al., 1986 (Table V), concluded that larvae are the most sensitive life stage, and they were killed by lower

concentrations and shorter exposures than eggs or adults.

Table IV. Marine-organism sensitivity to seawater-soluble-petroleum fractions.

Concentration	Effect	Life stage
1-100 ppm	lethal	adult
0.1-1.00 ppm	lethal	larvae, some eggs
0.01-1.0 ppm	sublethal	adult, larvae

Sources: Moore and Dwyer, 1974; Thorsteinson, 1984; USDOL, MMS, 1985a; and Laevastu et al., 1985.

The adhesion of oil droplets on developing herring eggs appeared to result in an increase in the occurrence of larval deformities, suggesting that developing eggs with adhering oil droplets may be exposed to higher concentrations for a longer period of time than those exposed to low levels (<4.7 ppm) of WSF (Pearson, 1985).

Laevastu et al., 1985, surveyed the oil-effects literature and concluded that for marine eggs and larvae, mortalities and serious sublethal

effects can be observed at WSF concentrations of 100 parts per billion (ppb).

Concentration (Table VI). This variable can be divided into three components, floating oil, i.e., on the sea surface or stranded; oil in the water column as dispersed and dissolved oil; and oil in bottom sediments.

Table V. Results of herring-oil challenge experiments conducted by Rice et al., 1986.

Lifestage	Duration	Concentration	Result
Prespawm Adult	2 days	2.3 ppm	LC ₅₀
	12 days	2.3 ppm	LC ₅₀
Eggs in Adult	12 days	1.8 ppm	Normal Hatching
Eggs	2 days	6.3 ppm	Normal Hatching
	12 days	1.8 ppm	LC ₅₀
Yolk-sac Larvae	<6 hours	6.8 ppm	Survived
	16-164 hours	2.8-2.3 ppm	LC ₅₀
Larvae	7 days	1.8 ppm	LC ₅₀
	21 days	0.96 ppm	LC ₅₀
	7 days	0.3 ppm	Growth Reduced
	NA	NA	Growth Rates Not Reduced by a Diet of Oil-Contaminated Prey

An oil slick is broken into discontinuous patches by wind and wave action. The area covered by the oil patches is much greater (10-100 times) than the area covered by the initial oil slick. In the experiment conducted by Payne et al., 1984, Prudhoe Bay crude oil formed a stable emulsion within 48 hours under simulated wind conditions of 2 m/s.

Table VI. Maximum area affected by a 10,000-barrel oil spill, assuming that 100 percent of the oil remains on the surface, in the water column, or deposited in bottom sediments.

Floating Oil Slick, Contiguous ¹	16 km ²
Floating Oil Slick, Noncontiguous ¹	18 km ²
Oil in Water Column ²	548 km ²
Oil in Bottom Sediments ³	2,730 km ²

¹ A contiguous slick 1 mm in thickness.

² A water-in-oil emulsion dispersed to 100 times the initial size.

³ Oil in the water column (dispersed and dissolved) at a concentration of 0.1 ppm, 5 m thick.

⁴ Oil in bottom sediments at a concentration of 8.1 ppm.

Figure 9 indicates that the concentration of petroleum hydrocarbons in the water column reaches a maximum within the first 24 hours following a spill. The concentration then decreases rapidly over the next 12 days. After 9 days, the concentrations of hydrocarbons in the water column will decrease to less than 0.1 ppm.

Observations made following the Exxon Valdez oil spill showed that the concentrations of volatile aromatic

hydrocarbons (VOA) in the water column had returned to near background levels, 0.20 ppb (Fig. 10), within a month. Continued weathering of the oil and flushing of water from Prince William Sound were considered important factors in reducing the concentration of VOA in the water column.

Table VII. Estimated time that herring eggs and larvae could be exposed to concentrations of hydrocarbons exceeding 0.1 ppm.

Source	Duration (Days)
Floating Oil	0 (<1)
Oil in Water Column	5
Oil in Sediments	> 1-Year

Sources: Payne, 1984; Threlkington, 1984; and Holt, 1990.

Table VII provides an estimation of the length of time that herring eggs and larvae could be exposed to levels of hydrocarbons exceeding 0.1 ppm.

Herring eggs can be directly affected by contact with floating/stranded oil (smothering of eggs), dispersed or dissolved oil (toxic effects), and oil in bottom sediments.

Few if any herring eggs spawned in Port Moller will be exposed to floating oil because they are deposited subtidally, on marine vegetation. Exposure to floating oil is further reduced because floating oil tends to become stranded high in the littoral zone during high tides and storm surges, where it is incorporated in beach sediments. The oil, however, may persist as pancakes or tarballs for over a year and could expose to floating oil a portion of two year-classes of herring spawning in Port Moller.

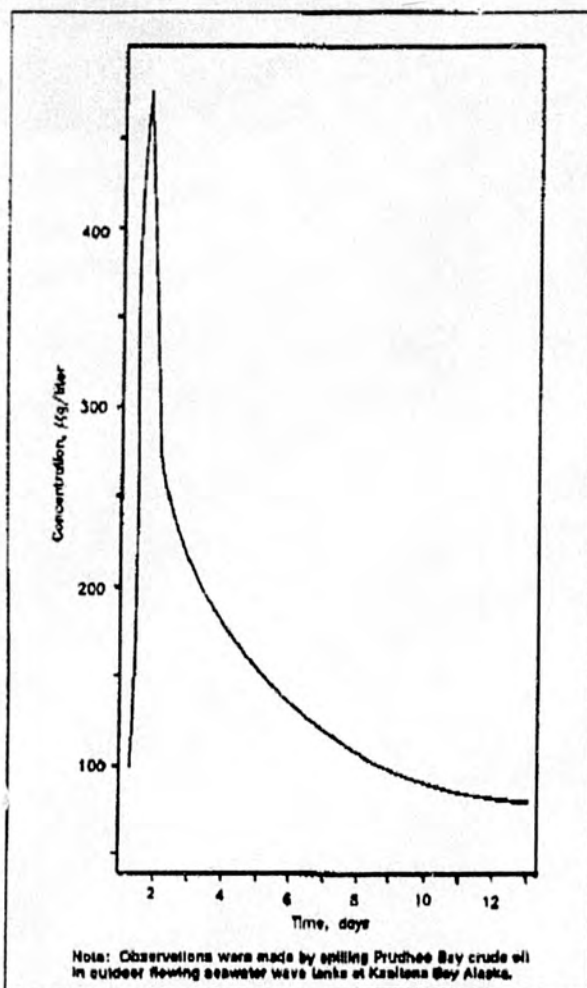


Figure 9. Observed concentrations of petroleum hydrocarbons in a moving water column under a slick of crude oil (Payne et al., 1984).

is weathered and contains low levels of VOA's and PAH's. The residence time for significant amounts of sedimented oil in offshore areas appears to be about a year. Inside the Port Moller estuary, residence times are expected to be shorter in shallow areas because of the comparatively higher energy and approaching a year in deeper areas because of comparatively lower energy levels (Thorsteinson, 1984).

R_{resources} Estimates of herring resources at risk in Port Moller are presented in Table VIII.

The length of time that eggs and larvae could be exposed to concentrations of dispersed and dissolved oil is a function of the oil-weathering and -flushing rate for Port Moller. Neff, 1990, observed a similar process in Prince William Sound when within 30 days following the spill, the concentration of toxic compounds returned to background or near-background levels. Therefore, the duration of exposure to maximum levels of hydrocarbons in Port Moller is expected to be less than 30 days. Observations by Payne, 1984, suggest that the concentration of hydrocarbons in the water column will decrease to less than 0.1 ppm within 9 days following a spill.

Oil that is incorporated in bottom sediments

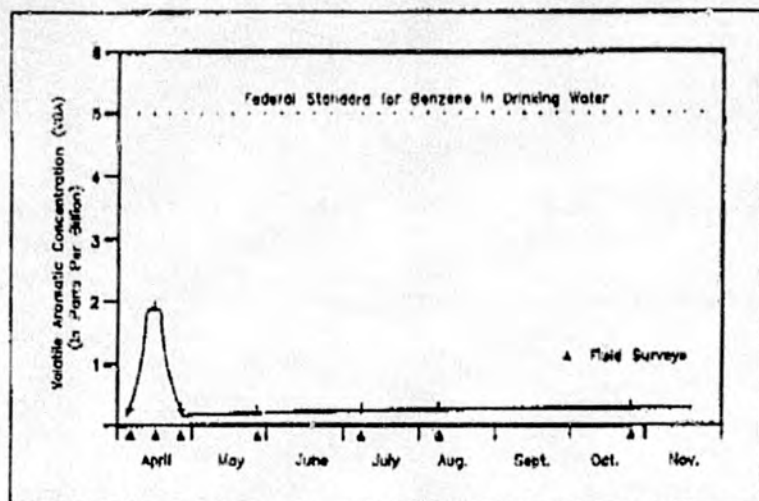


Figure 10. Average volatile aromatic concentrations from primary sites in Prince William Sound (Neff, 1990).

Table VIII. Potential spawning and rearing habitat and spawning biomass that could be affected.

Spawning Habitat ($H_{spawning}$) (Estimated Spawning Habitat)	24 km ²
Rearing Habitat ($H_{rearing}$) (Estimated Area of Moller and Herendeen Bays)	438 km ²
Estimates Herring Spawning Biomass	
Based on 1988 aerial survey	1,764 mt
Based on larval abundance	1,764 to 2,241 mt

Sources: McGurk, 1989b, and McGurk, In Press.

$H_{spawning}$: Information provided by McGurk, 1989, was used to estimate the aerial extent of eelgrass and rockweed beds (24 km²) in Moller and Herendeen Bays that have been associated with spawning herring in the past (Table VIII).

$H_{rearing}$: Specific information on the amount of optimum rearing habitat for herring larvae in the Port Moller estuary is not

available. However, information provided by McGurk, 1989, indicates that larvae tend to concentrate in Moller and Herendeen Bays. Therefore, these bays are considered prime rearing habitat. These two bays cover over half of the estuary, or about 438 km² (Table VIII).

Biomass. Estimates of the biomass of herring spawning in the Port Moller estuary range from 1,764 to 2,530 (Laevastu, 1985) and 1,768 to 2,241 (McGurk, In Press). The adults have been observed throughout the estuary (Table VIII).

OIL-SPILL ASSUMPTIONS

Table IX lists the assumptions used in analyzing the potential risk to spawning Pacific herring and herring eggs and larvae in Port Moller, Alaska, from an offshore oil spill. This evaluation is based on the assumption that a median-sized oil spill will occur during the WMV and that it will occur on or near tracts currently under lease by MMS for oil and exploration (Fig. 1). The joint probability (Table II) of a median-sized oil spill occurring and that it would occur during the WMV were not factored into this analysis.

Table IX. Oil-spill-evaluation assumptions.

P _{event}	
P _{oil spill}	1 Spill
P _{WMLV}	10%
P _{transport}	
P _{to coast}	13%
P _{into estuary}	20%
Q _{amount}	10,000 bbl
Q _{floating}	7,000 bbl
Q _{in water column}	2,800 bbl
Q _{in bottom sediments}	100 bbl
Q _{concentration}	
Q _{floating}	1 mm thick x 100 (dispersion rate)
Q _{in water column}	0.1 ppm to a depth of 5 m
Q _{in bottom sediments}	0.1 ppm per m ³
Q _{size (partitioning)}	
Q _{floating}	11.2 km ²
Q _{in water column}	153 km ²
Q _{in bottom sediments}	27 km ²
D _{disposal}	30-Day Maximum
D _{floating}	8-Days
D _{in water column}	5-Days
D _{in bottom sediments}	0-Days
H _{spawning}	24 km ²
H _{rearing}	438 km ²
B _{omass}	1,784 mt

It is assumed that there is a 13-percent probability that oil could reach the coast within 4 days and that the probability of oil entering Port Moller is 20 percent (Table IV).

A 10,000-bbl oil spill was assumed to be representative of the median-sized oil spills occurring on the OCS and is similar in size to a spill evaluated in the North Aleutian synthesis report (Table V). Based on information provided in Figure 5, 70 percent (7,000 bbl) of the oil would be floating or stranded after 4 days. After 10 days, 28 percent (2,800 bbl) would be dispersed or dissolved in the water column and 1 percent (100 bbl) would reside in bottom sediments.

Assuming that northeasterly winds prevailed for at least 4 days following the spill, 13

percent (1,300 bbl) of the oil could reach the coast. Of this amount, 70 percent or 910 bbl of the oil could be floating (based on 4 days of weathering), 28 percent or 384 bbl of the oil could be dispersed and dissolved in the water column (based on 10 days of weathering), and 1 percent or 130 bbl could be in bottom sediments (based on 10 days of weathering). The 4- and 10-day partitioning estimates were used to provide conservative estimates of the size of the areas that could be affected by an offshore oil spill.

For the purpose of this analysis, the area directly affected by floating oil was estimated by assuming that the oil spread to a uniform thickness of 1 mm and that the oil was dispersed into patches or windrows affecting an area about 100 times the undispersed size of the oil slick. The author assumes that the majority of the floating oil that enters Port Moller will be in the form of a stable water-in-oil emulsion and that it will become stranded along the high-tide line, where it will become incorporated in the beach sediments to slowly release petroleum hydrocarbons into the marine environment. Because the amount of oil that could be released into the estuary is assumed to be negligible, considering the weathered state of the oil and the amount that could be involved, it is not considered in this analysis.

The critical, i.e., lethal, concentration of oil in the water column and bottom sediments was assumed to be 0.1 ppm (Table V). To provide a conservative estimate of potential effects, oil dispersed and dissolved in the water column was assumed to be concentrated within the top 5 m. McGurk (1990, pers. commun.) observed concentrations of young herring larvae in this depth strata at night. Port Moller herring resources that could be affected by an oil spill were divided into three life stages: pre-spawning adults, spawned eggs, and larvae. The maximum

period of time that pre-spawning herring adults, spawned eggs, and larvae could be exposed to concentrations of oil exceeding 0.1 ppm is assumed to be about 30 days (Figs. 9 and 10). Since herring eggs in Port Moller are deposited subtidally and larvae do not reside on the surface, it is assumed that the duration of their exposure to floating crude oil would be minimal (0). Figure 9 indicates that pre-spawning adults, eggs, and larvae could be exposed to 0.1-ppm levels of dispersed and dissolved hydrocarbons for up to 9 days following an oil spill. Since in this analysis spilled oil would take about 4 days to reach Port Moller, the expected duration of exposure of fish, eggs, and larvae to oil in the water column would be shortened to about 5 days. Adult and larvae herring are not associated with bottom sediments; therefore, their exposure is assumed to be minimal (0). Since herring eggs are deposited primarily on marine vegetation and not on bottom sediments, their exposure to oiled sediments is also assumed to be minimal (0). However, a small but unknown portion of the eggs may be deposited on bottom substrate during the mass spawning process and, therefore, could be exposed to contaminated sediments.

The portion of the herring resources considered to be at risk from an offshore oil spill was assumed to be that portion of the habitat occupied by pre-spawning adults, eggs, and larvae. A conservative biomass estimate (1,784 mt) of pre-spawning adult herring in Port Moller was used in this analysis. The habitat occupied by the pre-spawning adults is expected to be similar to that used by the larvae (438 km²). The aerial extent of potential spawning and rearing habitat was used to estimate the portion of spawned herring eggs and larvae that could be exposed to spilled oil. The estimate of spawning habitat available was based on

an estimate of the aerial extent of marine vegetation (24 km²) in areas where large numbers of herring larvae were collected and where spawning had been observed in the past. The extent of rearing habitat was based on the observation that most herring larvae were observed in Moller and Herendeen Bays; and because the bays account for about half of the area of the Port Moller estuary, the rearing habitat was estimated to include about half of the estuary, or about 438 km².

RESULTS

Table X presents a summary of the potential effects that could result from a 10,000-bbl oil spill offshore, off of and upstream from Port Moller.

Assuming that northeasterly winds prevailed for at least 4 days following the spill, 13

Table X. Potential effects of a 10,000-barrel crude-oil spill on herring resources in Port Moller, Alaska.

P event	
P oil spill	67%
P WMLV	19%
P transport	
P to coast	13%
P into estuary	20%
O amount entering Port Moller	280 bbl
O floating	182 bbl
O in water column	73 bbl
O in bottom sediments	3 bbl
O fate	
O floating	9.8 km ²
O in water column	4 km ²
O in bottom sediments	1 km ²
D exposure	30-Day Maximum
D floating	0 Days
D in water column	8 Days
D in bottom sediments	0 Days
H spawning	24 km ²
Potential portion of spawning habitat affected	17%
H rearing	438 km ²
Potential portion of rearing habitat affected	1%
B biomass	1,784 mt
Potential portion of spawning biomass affected	1%

* Based on the assumption that the spilled oil will reach Port Moller within 10 days and that it will have reached a stable water-in-oil emulsion by the fourth day.

percent (1,300 bbl) of the oil could reach the coast. Of this amount, 20 percent (260 bbl) would enter the Port Moller estuary. Of this 20 percent, 70 percent (182 bbl) of the oil would be floating, 26 percent (73 bbl) would be in the water column, and 1 percent (3 bbl) would be in the sediments. Floating oil could cover an area of about 0.5 km², oil dispersed and dissolved in the water column could affect an area of about 4 km², and 1 km² of bottom sediments could be affected. The duration of exposure of the herring resources to floating oil and oiled sediments was assumed to be zero, and exposure to oil in the water column was expected to be about 5 days. The analysis also indicates that approximately 17 percent of the spawning habitat and 1 percent of the rearing habitat could be exposed to critical levels of oil in the water column.

DISCUSSION

While it is possible that large quantities of oil from an offshore oil spill could enter the Port Moller estuary and could affect herring resources, results of this analysis suggest that if an oil spill occurred on or near offshore areas currently under lease for gas and oil exploration in the southeastern Bering Sea during the period when herring resources were most vulnerable to the potential effects from spilled oil, the probability of a significant effect to these resources is quite low. The primary variables that reduce the probability of a significant effect to the herring resources are distance and time.

The distance separating the spill site and the resource at risk determines the minimum time required for the spilled oil to reach the resource in question. This in turn determines the maximum amount and condition of the oil that could reach the resource at risk. The condition and amount of oil reaching the resource determines the toxicity of the oil and the portion of the resource that could be exposed to toxic levels of spilled oil.

The probability of an offshore oil spill having a significant effect on herring resources in Port Moller is probably less than that described in this analysis because the analysis did not consider the probability that the spill would occur during the WMV, that dispersed and dissolved oil would be distributed throughout the mixed layer rather than just the top 5 m, and that there are multiple herring spawnings each year.

Considering the oceanographic dynamics of the estuary, all of the herring resources in the estuary could be exposed to varying concentrations of dissolved and dispersed oil in the water column for varying periods of time. Observed concentrations of hydrocarbons seldom would approach 0.1 ppm and would generally be much less. Therefore, the observation that specific portions of the resources could be exposed to 0.1 ppm for up to 5 days is considered to be a worst-case possibility.

Results from studies of herring eggs and larvae conducted following the Exxon Valdez oil spill indicated that the presence of spilled oil had no measurable effect on hatching success, occurrence of abnormal larvae, or larval growth and mortality rates (McGurk, 1990a,b). These results suggest that the developing eggs and resulting larvae were exposed to levels of dissolved and dispersed oil less than that needed to elicit an acute response, i.e., death, deformity, or reduced growth rates.

Although results from histopathological studies conducted following the Exxon Valdez oil spill have not been released, it appears that even though fishes

examined exhibited no overt response to the presence of spilled oil, hydrocarbons metabolites in liver bile and elevated levels of mixed function oxidases (MFO) were detected (anonymous comments made during discussions following the presentation of this paper). Therefore, even though hydrocarbons could be present in Port Moller following an oil spill at levels too low to elicit an acute response, sublethal effects could be observed for an extended period of time. Sublethal amounts of hydrocarbons could leach into the estuary from crude oil stranded in the littoral zone or be resuspended from bottom sediments during storm events. The presence of sublethal concentrations of hydrocarbons could probably be detected as elevated levels of hydrocarbons metabolites in liver bile and MFO enzymes. The long term effects from exposure to sublethal concentrations of hydrocarbons is unknown. However, the observation that spawning populations of Pacific herring are found in areas where chronic hydrocarbon pollution is endemic, i.e., San Francisco Bay, Puget Sound, etc. suggests that herring populations are able to tolerate exposure to sublethal concentrations of hydrocarbons that exceed those expected to occur in Port Moller following an offshore oil spill.

The study upon which much of the information used in this analysis is based was developed through the MMS-funded study, "Fisheries Oceanography of the Southern Bering Sea and North Aleutian Basin: Relationship of Larval Dispersion and Mortality of Herring Larvae to Environmental Conditions in the Port Moller Estuary," by Michael McGurk of Triton Environmental Consultants Ltd., Sidney, British Columbia (McGurk, 1990c).

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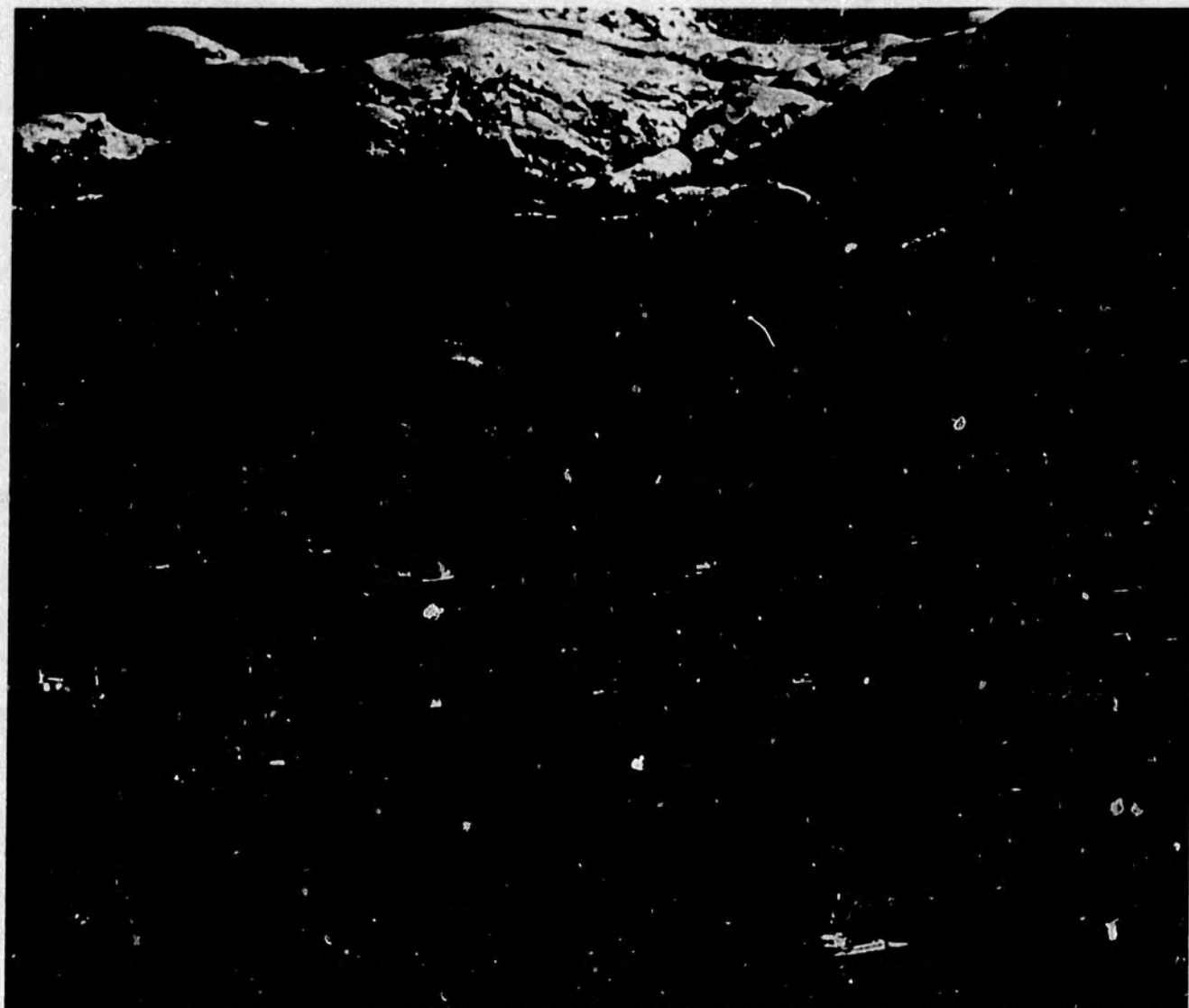
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Alaskan Fisheries

Two Years After the Spill



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February 1991

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PREFACE

This background paper responds to concerns that the 1989 *Exxon Valdez* spill might have damaged Alaska's fisheries, which are vital to the area's economy and lifestyle. It describes the robust condition of Prince William Sound fisheries and future prospects for seafood harvesting in Alaska. It does not include results of any of the research that has been conducted in Prince William Sound since the spill, but relies on the 1989 and 1990 commercial fishing results, the thousands of previously published scientific studies of oil in the sea, and the history of fishing after major spills in other regions.

The four authors all have extensive experience with Alaska's fisheries:

William F. Royce, Ph.D., Professor Emeritus of Fisheries in the College of Ocean and Fishery Sciences of the University of Washington in Seattle and retired executive of the U.S. National Marine Fisheries Service. For many years, he has studied fisheries management and the fish species of Alaska.

Thomas R. Schroeder, a fisheries consultant based in Homer, Alaska. He recently retired from the Alaska Department of Fish and Game, where he served as commercial fisheries management biologist for part of the area affected by the oil spill.

A.A. "Ole" Olsen, an Anchorage fisheries consultant and former fisherman, bush pilot and manager of seafood-processing plants throughout Alaska. In 1989 and 1990, he reviewed results of scientific studies (which he helped conduct) of the area's fish stocks with Alaskan villagers who rely on fish for subsistence. In addition, he participated in 1990 fishery-related spill cleanup activities.

William J. Allender, a former commercial fisherman and owner/operator of a sport fishing business based in Cordova Harbor in Prince William Sound. In 1989, he participated in Exxon's wildlife rescue programs. In 1990, as a consultant to Exxon, he worked with the Alaska Department of Fish and Game to help ensure the safe operation of Prince William Sound fisheries.

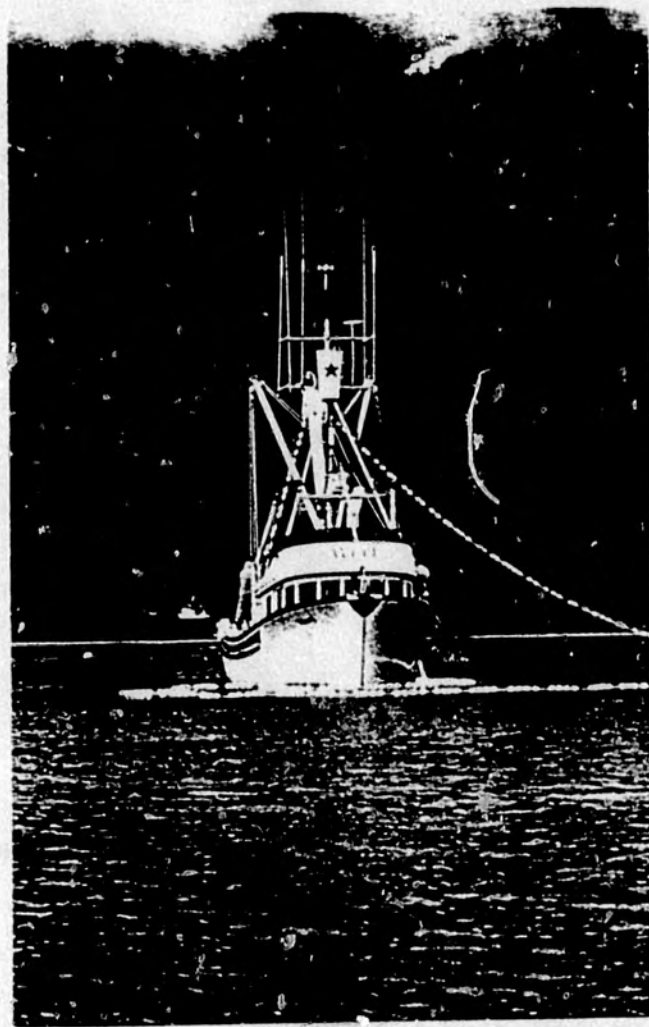


TABLE OF CONTENTS

1

Summary and Conclusions

page 3

2

Impact of the Spill

page 5

...on Water Quality

...on the 1989 Fisheries

...on the 1990 Fisheries

3

Salmon and Herring: the Litmus Tests

page 9

Pink Salmon

Implications for Other Salmon

Pacific Herring

4

Other Fisheries in Alaska

page 17

Subsistence/Personal-Use Fishing

Shellfish/Bottomfish

Sport Fisheries

5

Scientific Information From Earlier Oil Spills

page 21

The Exxon Claims Program

page 24

Questions and Answers

page 25

Appendix

page 28

Commercial Fisheries in Alaska

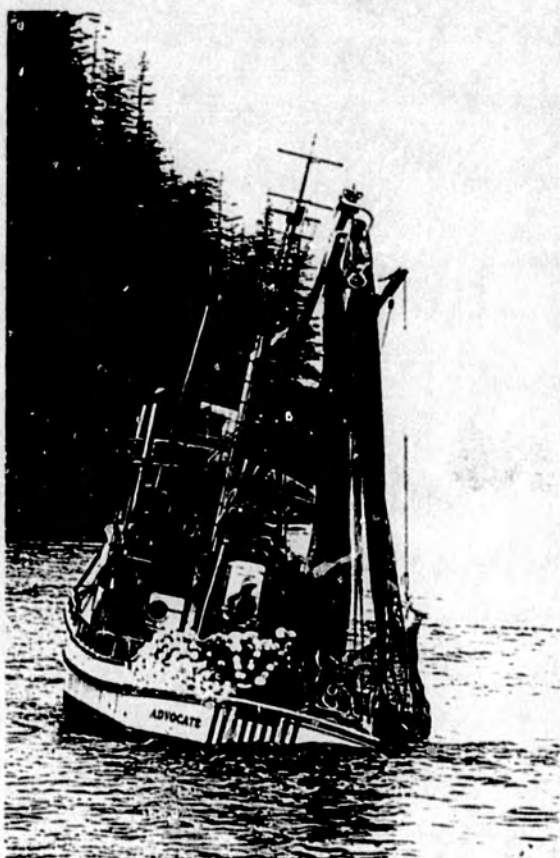
Alaska's Management of Commercial Fisheries

References

page 31

Biographical Sketches of the Authors

page 34



*In 1990, fishermen caught
44.2 million pink salmon
in Prince William Sound,
far eclipsing the previous
record of 29.2 million fish.*

1

SUMMARY AND CONCLUSIONS

In March 1989, the tanker *Exxon Valdez* struck a submerged reef off Bligh Island in Alaska's Prince William Sound, spilling about 11 million gallons of North Slope crude oil onto the waters. As the slick spread, anxiety also spread among the local commercial and sport fishing industries. Many fishermen worried whether the spill had ruined their livelihoods forever.

Within a year and a half, however, the commercial and sport fishing industries could move beyond the pessimism following the spill. During the 1990 season, commercial fishermen in Prince William Sound enjoyed record-breaking catches. In April, purse seiners netted 8,300 tons of herring — more than the entire year's "harvest quota" — in just 20 minutes, though the season typically lasts several hours. Then, over the summer, fishermen caught 44.2 million pink salmon, far eclipsing the previous record of 29.2 million fish.

The ample stocks of herring and pink salmon were significant to the sport and commercial fishermen for several reasons. Economically, the area's fishermen have traditionally harvested both pinks and herring in large numbers, and they rely on them for a major portion of their income. Biologically, the two species are considered more vulnerable to adverse effects of the oil than other species. The record-breaking harvests therefore have positive implications for less vulnerable species, including such favorites as halibut and king and coho salmon.

In spite of the accident, the sport and commercial fishing industries fared better in 1989 than originally anticipated. State officials concluded that sport fishermen would avoid oiled areas, and they did not restrict sport fishing in any way. Alaskan officials did close many of the spill area's prime commercial fisheries following the spill in order to eliminate any risk of marketing fish contaminated by oil-fouled nets or other gear. Although this action did force many fishermen to abandon their traditional fishing grounds, the total 1989 pink salmon harvest in Prince William Sound was still the fourth highest on record,

bringing in 21.9 million fish worth an estimated \$33.3 million. Statewide, commercial fishery production totaled \$1.3 billion, the second largest ever.

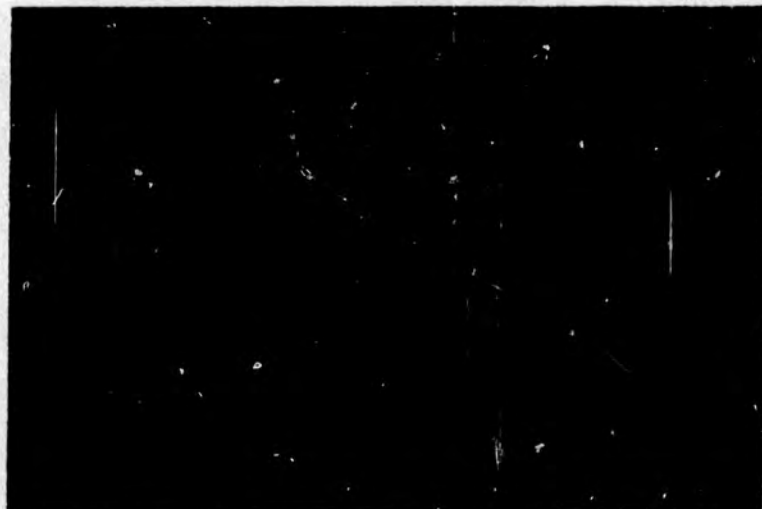
The area's commercial fishermen received financial compensation based on losses resulting from the various 1989 fishery closures. As of year-end 1990, Exxon had paid \$169 million to local fishermen in response to 1989 claims, and another \$133 million had been committed to seafood processors and related industries.

Many of the local fishermen assisted with the oil spill cleanup during the two summers following the accident. Because of their knowledge of the remote area, the fishermen proved invaluable to Exxon's cleanup operations and wildlife-rescue programs. Exxon paid more than \$105 million in wages and chartering fees to 1,440 individuals and firms that also received compensation for damages. This group includes 1,160 local commercial fishermen.

The potential long-term impact of the oil spill on fish is under careful study, but it is unlikely that any significant adverse effects on finfish populations will be discovered. Throughout 1989 and 1990, there were no confirmed reports of large fish mortalities, oil tainting, or contamination of commercial seafood products from the spill. In addition, long-term damage to finfish has not been documented in the hundreds of studies of earlier oil spills — many of which were larger than the *Exxon Valdez* spill.



*Oil from the spill
reached less than 20%
of the Prince William
Sound shoreline.*



2

IMPACT OF THE SPILL

Prince William Sound and the Gulf of Alaska constitute an enormous area, nearly 9,000 miles of coastline. Surveys showed that oil from the 1989 spill reached less than 20% of the Prince William Sound shoreline, and a small percentage of the Kenai peninsula, Kodiak Island, and Alaska peninsula shorelines. It spread into the western portions of the Sound and about 500 miles west to the Alaska peninsula and Kodiak Island (Maki, 1991).

Impact of the Spill on Water Quality

About one-third of North Slope crude oil consists of volatile hydrocarbons, which are relatively toxic, but almost all of them evaporate into the atmosphere within a few days (Galt, 1990). Three days elapsed before any oil reached the shoreline, and by that time a significant portion of the volatile hydrocarbons had evaporated. The remaining two-thirds of the North Slope crude oil is predominately composed of less toxic materials — the object of the massive cleanup operations Exxon mobilized during the summers of 1989 and 1990.

Exxon engaged five independent research organizations to study the quality of water in Prince William Sound immediately following the spill. More than 2,300 samples were taken from 61 locations from March to October of 1989, including the most heavily oiled areas. The findings were published in 1990

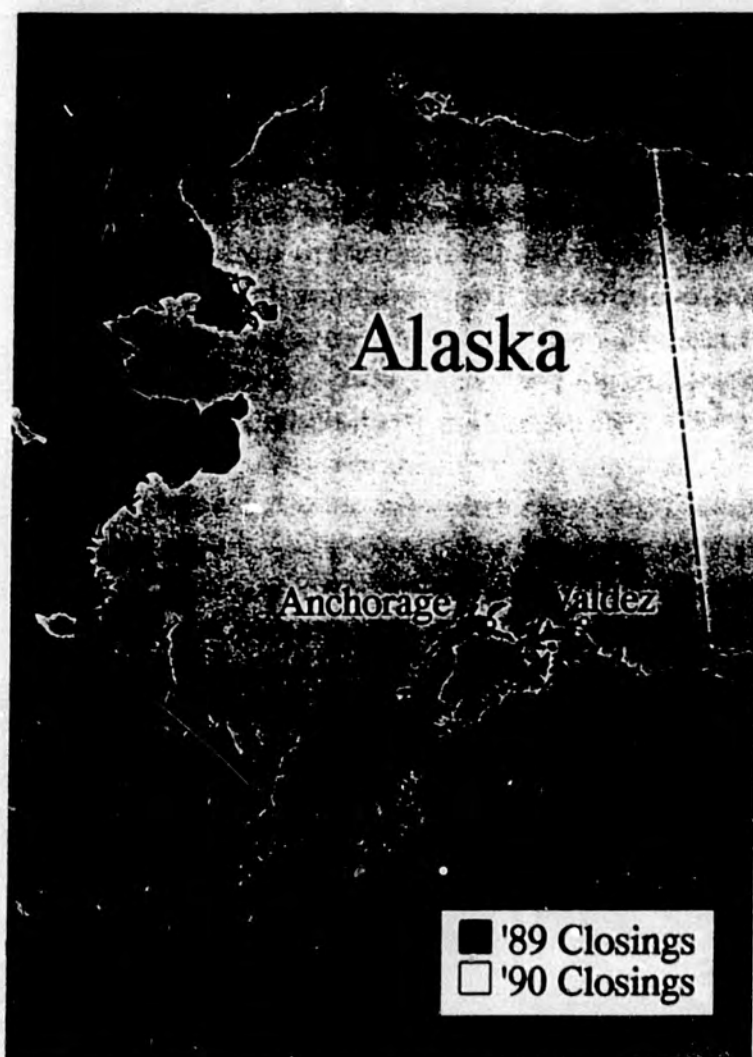


Today, the waters and shorelines of Prince William Sound and the Gulf of Alaska have been essentially cleansed of oil from the 1989 spill.

by Dr. Jerry M. Neff, senior research leader of Battelle Ocean Sciences, Duxbury, Massachusetts. His summation:

Fish kills have been reported after some oil spills, though it is important to note that there have been no verified reports of fish kills in Prince William Sound attributable to the oil spill...

Based on these observations from other spills, it is unlikely that there were effects of the oil spill on fishery species in Prince William Sound. Any effects would have



Portions of five (marked in red) of the state's 15 fishery management areas were closed at some point during 1989. By 1990, only two small areas (marked in yellow) in Prince William Sound had closings.

occurred in the few weeks immediately after the spill and would have been very localized and minor relative to fishery stock sizes and future catches. It is unlikely that any long-term effects directly attributable to the spill will be observed in terms of reduction in reproduction and early survival of fisheries species or in decreased fishery catch of any commercial species...

In most cases, the [hydrocarbon] concentrations measured in the Sound were at least 1000-fold lower than concentrations that are harmful to fish. Thus, the margin of safety for fish in Prince William Sound is very large and has grown larger as the concentrations of petroleum hydrocarbons in the water column have decreased over the summer and fall of 1989.

After two summers of cleanup and two winters of harsh storms and powerful waves, the waters and beaches of Prince William Sound were essentially clean at the end of 1990. Except for a few scattered sections with weathered residue, shoreline survey teams with representatives from the U.S. Coast Guard, Alaska's Department of Environmental Conservation, and Exxon did not find oil in August 1990.

Impact of the Spill on the 1989 Fisheries

In 1989, the Alaska Department of Fish and Game closed several commercial fisheries in order to prevent fish contaminated by oiled gear from reaching the consumer. The department



Prince William Sound's purse seiners netted 8,300 tons of herring — more than the entire year's harvest quota — in just twenty minutes, though the season typically lasts several hours. The State of Alaska's pre-season projected harvest was 6,300 tons of fish.

closed portions of five of the state's 15 fishery management areas (Savikko, 1990).

But, even with some areas closed to fishing in 1989, the statewide seafood harvest reached 5.2 billion pounds, with a value of \$1.3 billion — the second highest value at that time (Savikko, 1990). The 1989 Alaska harvest represented 38% of the total revenues from all United States commercial fisheries (USNMFS, 1990).

Immediately after the spill, Exxon and local fishermen gave the highest priority to protecting the salmon hatcheries, four of which are located in the spill area. Protective booms were placed around the hatcheries, and all of them remained totally free of oil. In Prince William Sound, protection of the hatcheries was considered especially vital to survival of the salmon fishery, which depends on hatchery-reared pink salmon fry for over 80% of the catch (ADF&G, 1990).

Impact of the Spill on the 1990 Fisheries

In 1990, as cleanup operations continued on isolated beaches, the fisheries operated normally in Prince William Sound and the Gulf of Alaska. Only two small areas were placed off-limits for the season; these were not prime commercial or recreational fishing areas, and there were no reports of fouled gear or contaminated fish attributable to the 1989 spill (ADF&G, 1990).

Although final figures are not yet available, preliminary Department of Fish and Game reports indicate that the statewide 1990 salmon catch may surpass the 1989 totals, partly because of extraordinary returns in Prince William Sound (Savikko, 1990).



3

SALMON AND HERRING: THE LITMUS TESTS

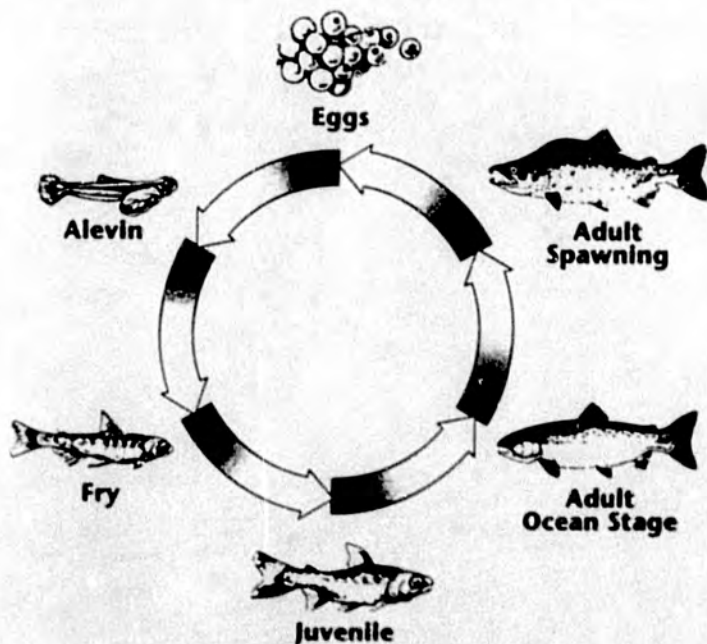
Two major Alaskan fisheries — pink salmon and herring “sac-roë” — warrant special attention because those species have traditionally been harvested in large numbers within Prince William Sound and because the spawning herring and the young of both pink salmon and herring were especially vulnerable to the oil spill.

Pink Salmon

Salmon species constitute a vital element of Alaska's economy and lifestyle. Salmon harvests provide the main source of revenue for the state's commercial fishing industry, the prime target of sport fishermen, and a basic component in the subsistence diet of many villagers.

Pink salmon, the most abundant Pacific salmon species, have a relatively simple two-year life cycle (see illustration), distinct from other salmon species. These fish are spawned in freshwater intertidal areas or streams. As fry, young salmon move into marine intertidal areas to feed before they head for open seas to mature as adults. After approximately two years at sea they return to their native streams to spawn and die.

Two-Year Life Cycle of Pink Salmon

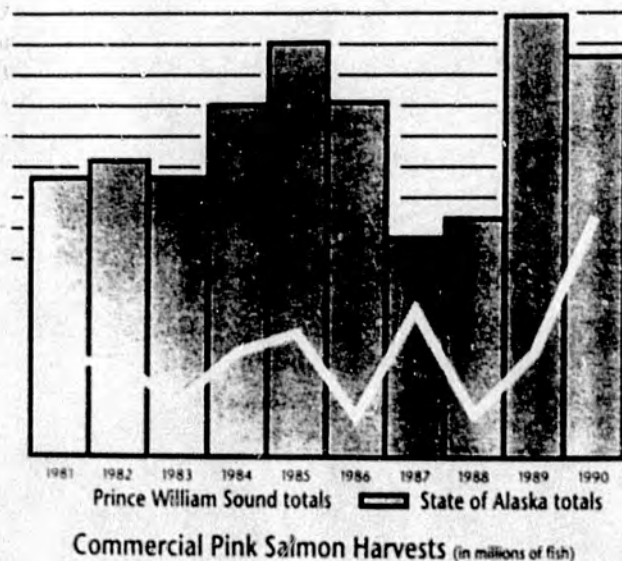


Pink salmon caught during the 1990 season in Prince William Sound have been found fry and are vulnerable after the oil spill.

The adult pink salmon harvested in August 1990 had emerged as fry into the intertidal areas of the Sound and Gulf of Alaska in April and May of 1989. They were heading to sea within a few weeks of the oil spill at a particularly vulnerable time in their life cycle when they would grow from about one-and-a-half inches to about three inches in length. Young pink salmon tend to remain close to shore during their first summer and move into deeper coastal waters in September (Hart, 1973). This migration pattern near the path of the spilled oil raised questions about the oil's possible effect on them.

Even under normal conditions, many unpredictable factors impact the survival rate of young fish, including weather conditions, predators, and the availability of food. The harvest of pink salmon is also subject to annual fluctuations.

In 1989, many commercial fishermen seeking pink salmon had to abandon their traditional grounds and seek waters that had not been closed by Alaska's Department of Fish and Game. As pink salmon swam out of the oiled areas, fishermen were able to catch them as they moved from closed to open areas. Despite the closings, 1989's total harvest in the Sound was 21.9 million pink salmon, with a value of \$33.3 million (Brady, 1990). It is the fourth largest pink salmon harvest on record and compares to 11.8 million fish in 1988 and 29.2 million fish in 1987 (Brady, 1990).



Fluctuations mark pink salmon catch totals in Prince William Sound and Alaska over the last ten years.

The statewide catch in 1989 totaled 96.5 million pink salmon, a record (see chart p. 10). Fishermen in 1989 received prices within the normal range for the decade (Savikko, 1990).

In establishing the catch limits for all salmon stocks, the state Department of Fish and Game attempts to allow an optimum number of fish to escape for spawning purposes. In 1989, because of the fishing limitations, state biologists estimated that in some streams more than the usual number of pink salmon escaped the fishing nets and went on to spawn. These larger "escapements" may be beneficial to those streams that have been depleted of breeding stock, many of which are in Prince William Sound, but a surplus could be wasteful in other streams. The impact of the 1989 escapement will not be known, however, until the pink salmon harvest of 1991 is completed.

By the time the 1990 salmon arrived, the state had removed restrictions on fishing in the spill-affected region, with two minor exceptions. Statewide, 87 million pink salmon with an average value of about \$1 each were caught (Engstrom, 1990). Prince William Sound accounted for 51% of the total with a catch of 44.2 million fish, breaking the 1987 record of 29.2 million fish (Brady, 1990). The average fish size was somewhat smaller than normal, 3.0 pounds versus a ten-year average of 3.5 pounds, which may be due to competition for food or to other marine habitat changes at sea.

In 1990, catches in the Lower Cook Inlet were about half the long-term historical average (Bucher, 1990). In the Kodiak management area, catches were below expectations (ADF&G, 1990). One possible factor influencing these results was a lower-than-expected return from the Tutka and Kitoi Bay hatcheries, neither of which was affected by the oil spill. Both of these low returns are not inconsistent with past harvests from these hatcheries. For example, the total Kitoi catch ranged from 301,000 fish in 1982 to 6,771,000 fish in 1989. Another factor was the closing of one district to salmon fishing for sockeye stock-management purposes, thus allowing a large number of pink salmon to escape the fishermen's nets.

State biologist James Brady called the 1990 pink salmon catch in Prince William Sound "a pleasant surprise." He credited

the catch to exceptional 1989 weather coupled with a plentiful plankton bloom to feed the young salmon (Villeneuve, 1990). Most significantly, the 1990 pink salmon catch should alleviate fears that the Alaska salmon fishery has been harmed by the spill.

Implications for Other Salmon

In addition to the pink (humpback) salmon, four other species of salmon are harvested commercially in Prince William Sound and the Gulf of Alaska — chinook (king), sockeye (red), coho (silver), and chum (dog). Because the harvest for pink salmon — the most vulnerable species — was bountiful, we are optimistic that the other salmon fisheries were likewise unharmed.

Oil did not threaten the spawning and rearing areas of the sockeye, chinook and coho salmon because they are located in freshwater lakes and streams far from the spill area. Unlike pinks, these species mature for one, two and sometimes three years in these areas before heading for the ocean. For example, the commercially important sockeye or red salmon is four or five inches long when it heads to sea as a one- or two-year old — much larger, older and stronger than the tiny pinks that head for salt water. If the spill did not harm the pink salmon fry of 1989, the larger sockeye juveniles were even more likely to survive. King and coho juveniles are even larger when they head to sea, averaging between five and seven inches in length (Hart, 1973).

In spite of the oil spill, the state of Alaska experienced a record salmon harvest in 1989, a catch of more than 153.3 million fish (Savikko, 1990). The 1990 statewide salmon catch was not affected by the oil spill and is expected to top 1989's total harvest after all the statistics are compiled. The preliminary 1990 catch figures include about 650,000 chinook, more than 52 million sockeye, 5.2 million coho, and more than 7.5 million chum salmon (ADF&G, 1990).

The statewide salmon harvest has increased significantly during the past decade because of improved management techniques, development of hatcheries, and favorable weather.

The catches of 1989 and 1990 — especially the 1990 pink salmon run in Prince William Sound — suggest that this favorable trend has not been affected by the oil spill.

Pacific Herring

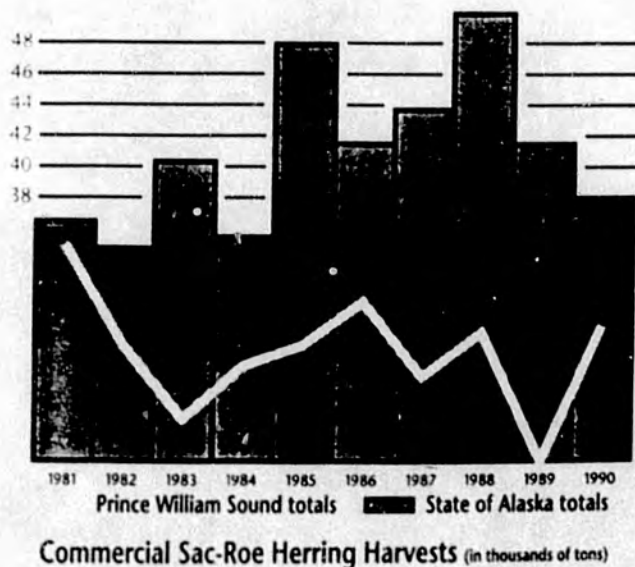
The Pacific herring is important to the Alaska fishing industry because its eggs or roe are sold in large quantities to the Japanese market and because, as part of the food chain, it is consumed by larger commercial species of fish such as salmon and halibut.

Herring are mass spawners and congregate in shallow areas (depths less than 35 feet) where eelgrass, kelp and other seaweeds can be found. From April to June, females deposit eggs. The eggs, which are sticky, adhere to underwater plants, rocks and other surfaces where they are fertilized by the males (Hart, 1973). Since herring spawn in such places, there was potential in 1989 for spawning fish or their eggs to become exposed to spilled oil.

The annual harvest draws from herring within a five-year age span. Thus, each year's catch is not dependent on a single year's successful survival, as with pink salmon.

In Alaska, there are four commercial herring fisheries. First, a small number of fish are caught for food and bait. Second, divers gather herring eggs or roe on kelp in shallow, open waters.

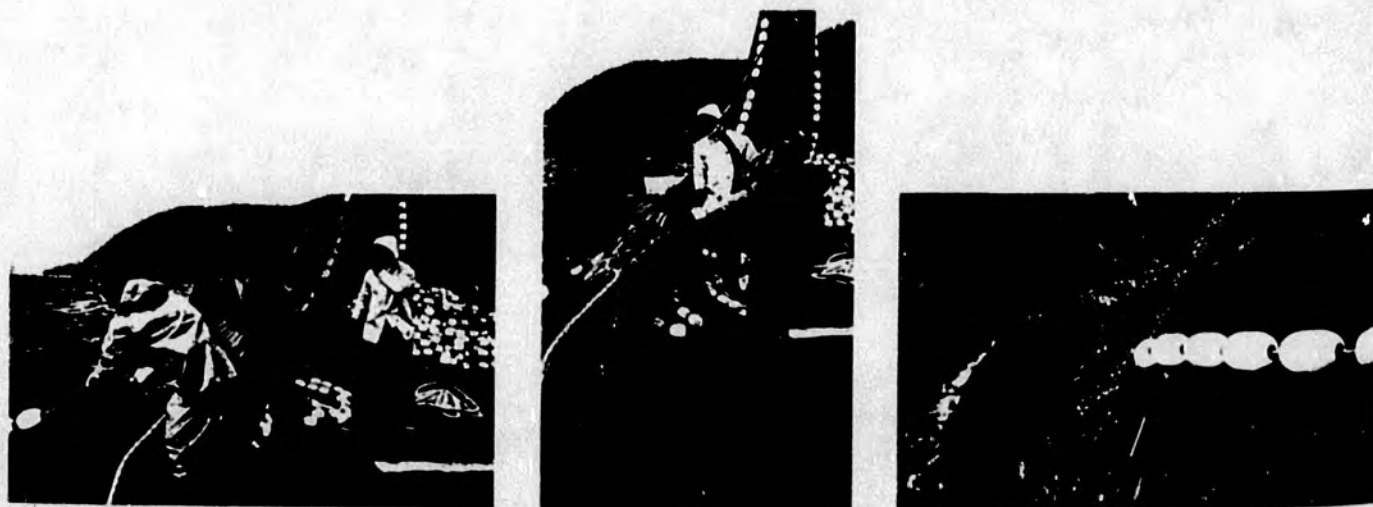
*Herring sac-ro
harvests fluctuate
from year to year.*



Third, roe is gathered on kelp in man-made enclosures (this is known as the pound-kelp fishery). The fourth and most important commercial harvest is the "sac-ro" fishery, in which herring are netted to collect the mature female's egg-filled membrane or sac. Each year the state limits the sac-ro harvest to 20% of the estimated herring stocks.

In 1989, the state closed Prince William Sound to the sac-ro herring harvest, which usually takes place in April. Nevertheless, the statewide sac-ro harvest was 41,387 tons with a market value of \$16.3 million — compared to 49,766 tons in 1988 (Savikko, 1990).

Most of the herring that spawned in Prince William Sound in 1989 were available to fishermen in 1990, since herring, unlike salmon, do not die after they reproduce. They continue to reproduce until they are nine years old or older. The bulk of herring harvested in Prince William Sound are three to seven years old. The 1989 crop of eggs will start returning as harvestable three-year-olds in 1992. Based on current population estimates by the Alaska Department of Fish and Game, prospects are encouraging for future herring harvests.



Prince William Sound was reopened to sac-roe fishing in April 1990, and the herring were so plentiful that fishermen netted 8,300 tons in 20 minutes, a harvest 32% higher than the pre-season projection of 6,300 tons (Brady, 1990; Savikko, 1990). That catch represented 22% of the statewide total harvest of 37,866 tons.

The successful Prince William Sound 1990 sac-roe harvest indicates that the herring population is thriving. Many of the fish caught in 1990 were spawning in Prince William Sound at the time of the oil spill.

Alaska's Department of Fish and Game has also recently measured a huge mass of herring in the Sound and is projecting a large harvest in 1991 (Brady, *et al.*, 1990). The healthy state of the herring fishery is not only significant from the standpoint of the oil spill, but it also shows that there will be a plentiful supply of herring as food for salmon, other large species of finfish, marine mammals, and waterfowl.

Prince William Sound's pink salmon harvest was a record in 1990, even though most of these two-year old adults had traveled through the Sound's waters as vulnerable fry in the months following the spill.





*This youngster and other
Alaskan villagers subsist
on the area's fish stocks.*



4

OTHER FISHERIES IN ALASKA

In addition to commercial harvests, there are two other important fisheries in Alaska — subsistence/personal-use harvesting and sport fishing. In contrast to the numerous 1989 commercial fishery closings, only one area had restricted subsistence fishing, and there were no restrictions on sport fishing. Government officials announced that the salmon and other finfish throughout the area were safe to eat.

Subsistence/Personal-Use Fishing

When the oil spill occurred, some 2,500 rural Alaskans feared that two of their food resources, fish and shellfish, were endangered (Fall, 1990). To assess the healthfulness of the subsistence seafood resources, joint scientific studies were undertaken by the National Oceanic and Atmospheric Administration (NOAA), the Alaska Department of Fish and Game (ADF&G), and Exxon. Fish and shellfish specimens for these studies were gathered from the most important subsistence resource areas, which were selected by representatives from the rural villages. These village leaders often accompanied the scientists collecting the samples. The State of Alaska and NOAA conducted all chemical or taste and smell tests on more than 900 halibut, 5,000 other finfish, and 300 shellfish samples collected for both subsistence and commercial food safety studies (ADHSS, 1989).

The tests showed that all finfish were safe to eat. Additional tests showed that the hydrocarbon content of smoked fish was substantially higher than the hydrocarbon content of seafood tested in Alaska following the 1989 spill. Some clams and mussels from a few areas with especially heavy concentrations of oil had elevated hydrocarbon levels, although several had been contaminated by refined petroleum products (*e.g.*, diesel fuel) from other sources, not by the 1989 spilled crude oil (Oil Spill Health Task Force, 1990).

Clams and mussels do not constitute a major part of the subsistence diet. Most Alaskans were already cautious about eating these seafoods because of the threat of paralytic shellfish poisoning caused by microorganisms known as "red tide."

Dr. Tom Nighswander, Director of the Alaska Native Health Service, founded the Oil Spill Health Task Force with members including the following organizations:

Alaska Department of Environmental Conservation
ADF&G
Alaska Department of Health and Social Services
Alaska Governor's Office
Exxon
Indian Health Service
Kodiak Area Native Association
NOAA
North Pacific Rim

On the task force's behalf, Dr. Nighswander asked the U.S. Food and Drug Administration (FDA) to conduct a complete food safety assessment based on the results of the NOAA/ADF&G tests. The FDA concluded that all the fish and shellfish, including those taken from the most heavily impacted areas studied, were safe for a lifetime of subsistence consumption (Quantitative Risk Assessment Committee, 1990).

Task force representatives traveled to the subsistence villages and advised residents: "The best tests to determine the safety of subsistence foods are performed by those who gather the food. If the resources smell or taste of petroleum, they should not be eaten. If they appear clean by these methods, they are almost certainly safe to eat."

Shellfish/Bottomfish

The findings for subsistence fisheries hold positive implications for the area's shellfish and bottomfish fisheries. Unfortunately, the commercial harvest of shrimp and crab in the Prince William Sound area had already ground to a near-halt because the stocks had been depleted by overfishing and consumption by sea otters (Savikko, 1990). Most of Alaska's crab are taken in the Bering Sea, far away from the spill area.

Likewise, the state's prime bottomfish areas are located far outside the reach of the spill, most of them beyond the three-mile limit of the state's jurisdiction. Alaska bottomfish,

which feed on the ocean floor, include halibut, pollock, cod and flounder.

Shortly after the spill, the state closed the waters of Prince William Sound and the outer Kenai peninsula to the harvesting of bottomfish. The areas were reopened to bottomfishing in July 1989. By this time, however, boats normally seeking these fish were either working on the cleanup operation or had shifted to other fisheries. There were no restrictions on halibut fishing in 1989, and the Alaska harvest was greater than it had been the previous year.

Sport Fisheries

Sport fishing for halibut, several varieties of salmon, char (Dolly Varden), cutthroat and lake trout, crab and shrimp provides Alaska with a significant share of its tourist and recreation income from May through September. It is a significant source of recreational enjoyment both for Alaska residents and for visitors from throughout the world. Salmon is the main lure, and the latest attraction is fly-fishing for sockeyes. The state is undertaking special programs to increase fish runs attractive to sportsmen, and it advertises that the Kenai River has the world's largest king salmon and that 450-pound halibut can only be caught off the Alaska coast.

The cold-climate wilderness mystique is attracting tourists to Alaska in ever-increasing numbers from all corners of the world. There has been significant improvement in access to



Sport fishermen continued catching and eating fish in the wake of the spill.

Alaska's fishing centers, and charter-boat touring is a thriving business in such ports as Cordova, Valdez and Whittier in Prince William Sound, and in Homer and Seward on the Kenai peninsula.

Statewide sport fishing rules apply to catch and possession limits, and waters are not normally opened or closed by regional officials on short notice. In the wake of the spill, the state's policies toward commercial and sport fishing were markedly different. While most of Prince William Sound was closed to commercial fishing boats in 1989, there was no prohibition on sport fishing in the same waters. In fact, according to the ADF&G, sport fishing activity in Prince William Sound set a new record in 1989. Activity was 71% higher than the average for the previous ten years (Whitmore, 1991).



State officials kept Prince William Sound open to recreational fishing in 1989 and 1990.

5

SCIENTIFIC INFORMATION FROM EARLIER OIL SPILLS

Based on extensive scientific studies of previous oil spills, such as those reported by the National Research Council of the U.S. National Academy of Sciences in *Oil in the Sea: Inputs, Fates and Effects*, no one should have been surprised by the successful 1989 and 1990 fish harvests in Prince William Sound and the rest of Alaska.

Other scientific literature that has been developed on the effect of oil in the oceans of the world also supports the National Research Council conclusions. The literature includes a 1990 review of scientific knowledge by the Congressional Research Service of the Library of Congress, a 1982 publication by the Royal Society, and a 1990 compilation of literature on the subject by four United Kingdom oil-spill specialists, *Natural Recovery of Cold Water Marine Environments After an Oil Spill*.

1989

Oil continues to plague fisheries
Anchorage Times July 2, 1989

Oil Spill Leads to Partial Salmon Fishing Closure
United Press International May 20, 1989

First Catch of Salmon Free of Oil but Fishermen Remain Wary as Vessels Move Westward
Anchorage Times May 24, 1989

Upper Inlet season delayed
Anchorage Daily News June 24, 1989

Outlook: Salmon Alaskans Face Uncertainties
August 1989
National Fishermen's West Coast Focus

Salmon Fishermen see Alaska Spill Dash Record Harvest Dreams
REUTERS
September 13, 1989

1990

Pink returns unexpectedly strong
Anchorage Daily News August 10, 1990

PWS harvest could top 40 million pinks
Kodiak Daily Mirror
August 22, 1990

Sockeye haul hits 3 million
The Associated Press
July 31, 1990

Record pace for returning Sound pinks
Anchorage Daily News
July 13, 1990

Record Pink Salmon Harvest Tallied in Prince William Sound
Sitka Sentinel August 20, 1990

Record catch of pinks expected in sound
Juneau Empire August 13, 1990

1989's dismal expectations contrast with 1990's headlines.

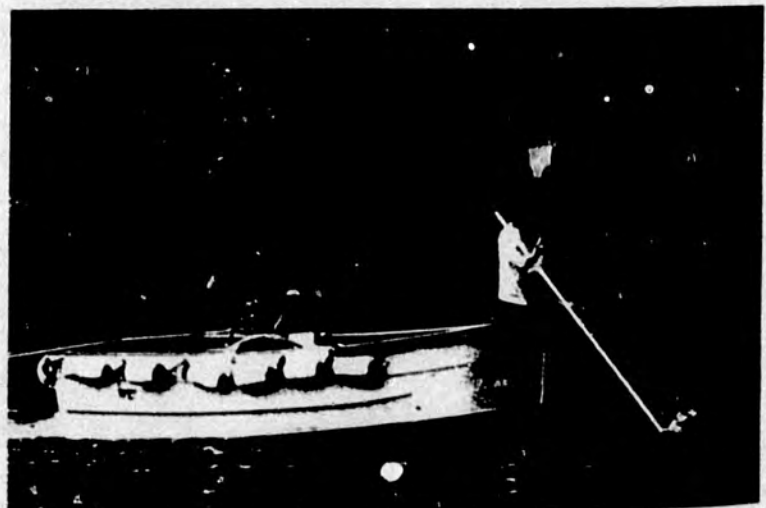
These publications identify more than 2,000 scientific papers that have been written on the subject. The conclusions:

For species of shellfish, finfish and waterfowl that are harvested, the mortality from an oil spill, so far as is known, has never come close to approaching the magnitude of the annual harvests (Mielke, 1990).

The most significant commercial impact of oil pollution is tainting of the catch, or fear that the catch may be tainted, but natural population fluctuations, or the effects of commercial fishing practices, or the insensitivity of the estimates of recruitment and stock size, mask any impact that losses from oil pollution may have (Clark, 1982).

Massive fish kills during oil spills probably have not occurred. Some mortalities have been observed at a number of spills, but generally only in limited areas, and then not in large amounts. Fish have the ability to move away from an impacted area, either laterally or by moving to a greater depth (National Research Council, 1985).

Annual recruitment of fish stocks fluctuates naturally, and the size of the catchable stocks is determined more by the activities of the fishing industry (e.g. overfishing) and by climatic changes than by any other factor (Baker, et al., 1990).



Finfish appear to have the capacity to detect chemical substances and avoid those that might be harmful. Scientists also believe that natural losses of eggs and larvae are normal and that losses, if any, caused by an oil spill would not be measurable.

In previous spills, kills of mobile adult fish have rarely been recorded. In 1978, the *Amoco Cadiz* spilled more than 70 million gallons of crude oil — six times the amount spilled by the *Exxon Valdez* — off France's Brittany Coast, and the only significant mortality was of fish that were trapped in the rocky, intertidal waters. Following the 1969 offshore oil rig blowout in California's Santa Barbara Channel, professional spotters observed the fish habitat from the air and recorded no heavy mortality of fish. Studies of numerous spills show that shellfish in shallow-water or intertidal sediments can be the most significant casualties of an oil spill (Baker, *et al.*, 1990).

Oil is not an unusual element in the fishery environment. In Alaska, there are 29 documented natural oil seeps that put an unknown quantity of crude oil into the water (Becker, 1988). Worldwide, the National Research Council estimates that naturally occurring seepage totals average 185 million gallons of oil a year. According to their 1985 report, the best estimate is that an average of more than one billion gallons of petroleum enter the world's oceans each year, but only about 10% of it comes from tanker accidents. This compares with 37% from municipal and industrial wastes, plus runoff from the land.

The existing body of research from previous spills and observations of the Alaska fisheries provide encouragement that the 1989 oil spill should have had no measurable effect on the size or quality of the harvest in 1989 or 1990, nor should it in the future.

THE EXXON CLAIMS PROGRAM

Within weeks after the *Exxon Valdez* spill, Exxon established claims offices in locations throughout the spill-impacted area so that any adverse economic impact on the fishing industry could be ameliorated. Claims adjusters gave advance payments to fishermen and others suffering hardship due to lack of income.

Through year-end 1990, Exxon reported that it had committed more than \$302 million in damage compensation on 12,300 claims. This includes \$169 million in payments to more than 7,300 commercial fishermen and individuals employed by fishing permit holders. An additional \$133 million was committed to about 5,000 claims to seafood processors, cannery workers, tender-boat owners, and other individuals and businesses affected by the spill.

A major portion of Exxon's payments was based on a set of "Salmon Permit Holders Claims Guidelines" that described the basis under which the company would pay holders of commercial salmon fishing licenses. The key guidelines:

"Individual permit holders will be compensated for their share of the pre-season ADF&G projected salmon harvest based on their two-year historical average share of the catch...prices used in final payments will be average market prices for the season."

The adjusters computed a catch value for each fisherman based on the size of the projected harvest and market price. As it turned out, the state's projections were high in Prince William Sound. Exxon made larger payments than were warranted by the size of the actual run. In Upper Cook Inlet, Kodiak and Chignik, however, payments were increased because runs were stronger than projected.

ROLE OF FISHERMEN IN THE CLEANUP

Fishermen who work in Prince William Sound and the Gulf of Alaska proved to be a major resource to Exxon and government officials in their cleanup and wildlife-rescue operations. These fishermen had vessels and equipment that were needed for the operations, and they had expert knowledge of tides and geographical features in the affected areas. The vessel owners and their crews towed booms to contain oil, transported technicians and workers to remote beaches, served as pilots on research boats, helped clean beaches, and rescued sea otters and seabirds.

Exxon paid significant amounts for these services. For example, Exxon hired 1,440 individuals and firms in 1989, including about 1,160 commercial fishermen-claimants, and paid them cleanup wages and vessel-chartering fees in excess of \$105 million in addition to the damage compensation they received.

Figures provided by Exxon Company, U.S.A.

6

QUESTIONS AND ANSWERS

The following are answers to questions the authors have been asked about the Alaskan fishery in the wake of the oil spill.

What might explain 1990's extraordinary Prince William Sound pink salmon and herring catches?

There was an unusually abundant plankton bloom in 1989, the largest on record, and this provided an extraordinary amount of food for the pink salmon that were harvested in 1990. The pink salmon harvest reflects the long-term trend of larger catches brought about by increased hatchery releases and a history of good management under the direction of the Alaska Department of Fish and Game. The herring harvest of 1990 included fish that would have been caught in 1989 when the Prince William Sound herring fishery was closed.

Your report concentrates on pink salmon and herring. What about other species of fish?

These two species were chosen because they are important commercially and because they have implications for other species. The record catches of pink salmon and herring are significant because their primary spawning areas are located in shallow intertidal areas that were in close proximity to the spilled oil, and because herring and pink salmon fry swam in the waters of the Sound soon after the spill.

Will the pink salmon and herring harvest levels in 1991 be related to the spill?

In view of the outstanding harvests of pink salmon and herring in 1990, there is no basis to expect any spill-related impacts in future harvests. Fish-harvest predictions are about as reliable as long-range weather forecasts; nature is very unpredictable.

Weren't there reports of significant fish kills immediately after the spill?

There were no verifiable ones. However, the state reported receiving a few dead rockfish at the time of the spill. These deaths are not known to be associated with the spill.

Why were there low pink salmon returns in the Lower Cook Inlet and Kodiak areas in 1990?

One explanation was a low return from the Tutka hatchery in Lower Cook Inlet and Kitoi Bay hatchery in Kodiak. These were not unusual since there has been an erratic pattern of returns from these hatcheries over the years. The poor 1990 returns were probably not associated with the 1989 oil spill since all hatcheries were protected from oil. Also, part of the Kodiak area was closed for sockeye management reasons, allowing a large number of pink salmon to elude the fishermen's nets.

Won't the 1989 "overescapement" — a surplus of spawners — hurt the salmon populations?

The potential impact of large escapements must literally be analyzed stream by stream, almost inch by inch. In some instances, too many fish entering spawning grounds may reduce the output of a stream. On the other hand, a heavy escapement would be beneficial to streams that are producing below historic levels.



Do hydrocarbons accumulate in fish?

No. Hydrocarbons are not like DDT or other toxins that accumulate through the food chain. Fish have the capacity to metabolize, or naturally break down, hydrocarbons and expel them from their systems.

Are some Alaska fish normally exposed to hydrocarbons?

Yes. There are known naturally occurring oil seeps along the Alaska coast. There has never been any indication that this constant petroleum has harmed a fishery.

What are the major threats to our nation's marine fish stocks?

The biggest problems by far are poor fishery management policies, which result in overfishing, and the incidental catch of protected species by those fishing for other species. With proper management strategies, the severity of these problems could be reduced significantly.



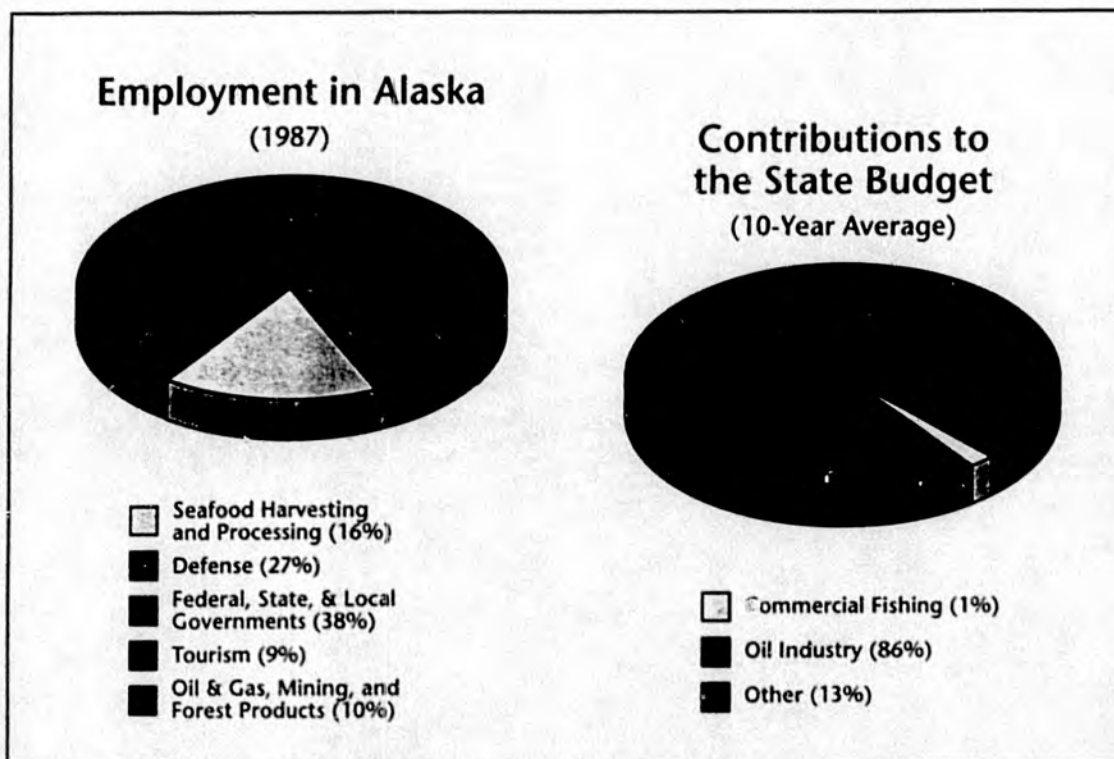
APPENDIX

Commercial Fisheries in Alaska

Alaska is by far the most important fishing state in the United States, accounting in 1989 for almost half the nation's catch in pounds and 38% in value. No other state comes close to Alaska in either category, according to statistics compiled by the U.S. Department of Commerce. The Alaska harvest includes salmon, herring, shellfish, pollock and halibut, with salmon and shellfish producing a majority of the value.

Alaska is a major exporter of fishery products. Seafood valued at \$561 million was shipped overseas in 1987, with all but 5% going to Japan. That represented one-third of the U.S. seafood exports.

The seafood industry is the largest non-governmental employer in Alaska, providing 16.4% of the state's jobs. A 1989 study prepared for the Alaska Seafood Industry Study Commission concluded that the seafood industry provides "nearly 70,000 seasonal jobs, which translates to 33,000 direct, indirect and induced year-round jobs." The report, written by the McDowell Group of Juneau, estimated total seafood industry payroll for 1987 at \$596 million.



Although the fishing industry is Alaska's largest private employer, the oil industry provides an average of 86% of state and local government tax revenue.

Although the seafood industry is the second largest source of state and local government tax revenue, it trails the oil and gas industry by a wide margin. According to media reports and a fiscal policy paper issued by the Institute of Social and Economic Research at the University of Alaska at Anchorage, oil production provides more than \$2.5 billion a year in support for state and local government, compared to about \$50 million in taxes on marine motor fuels and the harvesting of fish. The oil industry provides an average of 86% of total state government revenue.

Alaska's income from the oil industry is so great that the state pays each citizen an annual dividend known as a permanent-fund payment, which in 1990 amounted to \$952 per person. Anyone 65 or over who has lived in Alaska for one year is also entitled to a "longevity bonus" of \$250 a month. The Alaska revenue structure is highly unusual, with no personal income tax or state sales tax levied. In addition, local property taxes are approximately 20% below the national average.

Alaska's Management of Commercial Fisheries

Three decades ago, Alaska's commercial fisheries were described as the victim of a "pathetic history of ruinous exploitation." Until 1961, Alaska's fishery management was in the hands of the federal government, which allowed the industry to catch salmon and other fish "almost unrestrained," according to Dr. William F. Royce, one of the authors of this report, writing in the March/April 1989 issue of *Fisheries* magazine.

After the Alaska Department of Fish and Game took over management of the resource, conservationist steps were taken to limit commercial fishing licenses and to prevent depletion of the species. Today, Alaska has the best managed commercial fisheries in the nation because the state has "separated much of the politics of conservation from the politics of economics and equity," Royce wrote. The per-fish cost to Alaska for salmon management is only about 3% as much as the cost per fish in other Pacific coast states.

Aside from the restricted number of fishing licenses, the key to Alaska's management program is the unique emergency-order authority held by the chief management biologist in each fishery area to preserve the resource as well as the quality of Alaska's seafood products. Based on their unique knowledge of water conditions and fish population levels, biologists have the extraordinary power to open and close fishing areas minute by minute and stream by stream.

The state, which encompasses an area as large as one-third of the lower 48 states, is divided into 15 management areas, each with numerous districts and sub-districts. Fishing regulations vary from area to area, depending upon the conditions each biologist encounters. Close communication and cooperation between the state officials and working fishermen are a key to success of the program.

In the three decades of decentralized control, the state has essentially doubled the salmon run. Despite these controls, however, the size of each salmon run remains unpredictable since biologists never know how fish are going to survive in the ocean and return to their spawning grounds as adults.

Forecasting the annual catch of herring for the sac-roë puts fishery biologists to the supreme test. Where else do you find a fishery with perhaps a 20-minute open season? In Prince William Sound, the sac-roë season can range from less than half an hour to more than several hours, and a successful fisherman may have 300 tons of herring in his net — or may miss the season entirely. The sac-roë season must be short because herring gather in huge schools and a lengthy opening would result in severe over-harvest of the resource.

Following the spill, local biologists retained their autonomy over the opening and closing of the fisheries, but they were placed under a "Zero-Tolerance Policy" designed to guarantee that the quality of Alaskan seafood would not be questioned. The policy was stated in a memorandum of understanding between the two state agencies responsible for protecting the fishery, the Department of Fish and Game and the Department of Environmental Conservation. The key section:

A fishing area will remain closed if there is an indication of oil in any quantity in the area or proximity of the area (including beaches), such that there is an appreciable likelihood that gear will be fouled, fish harvest adulterated, or such that the conduct of an orderly fishery could not take place.

This stringent policy, which resulted in the closing of most of Prince William Sound, Lower Cook Inlet and Kodiak and portions of two other fishing areas in 1989, was designed to prevent adverse impacts on the perception of high quality that consumers associate with Alaskan seafoods. Although scientists indicated that finfish throughout the area would be safe to eat so long as fishing gear remained free of oil, the state elected a conservative policy that kept all commercial fishing vessels out of oiled areas.

In addition to closing fishing areas, the Alaska Department of Environmental Conservation and the U.S. Food and Drug Administration beefed up inspection activities on fishing vessels to guarantee that no fish were contaminated by crude oil. Inspectors were also deployed on fish-transport or tender vessels and in processing plants. Throughout the 1989 and 1990 seasons, there were no reports of fish contamination from *Exxon Valdez* oil on fishing boats, on tenders or in processing plants.

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BIOGRAPHICAL SKETCHES OF THE AUTHORS



William F. Royce, Ph.D.

A consulting fisheries scientist, Dr. Royce is a Professor Emeritus of Fisheries in the College of Ocean and Fishery Sciences of the University of Washington in Seattle and a retired executive of the United States National Marine Fisheries Service. After receiving his doctorate in zoology from Cornell University in 1943, he held a number of research and administrative positions for the Fish and Wildlife Service, including directorship of the Woods Hole (Massachusetts) Laboratory and assistant regional director in charge of research in Juneau, Alaska. In 1958, he became a fisheries professor and director of the Fisheries Research Institute at the University of Washington. During periods of leave, he was employed as a consultant on a variety of fisheries problems around the world. In 1972, he was appointed Associate Director in Charge of Resource Research for the National Marine Fisheries Service in Washington, D.C. Dr. Royce is the author of more than 100 scientific publications, including books entitled *Introduction to the Fishery Sciences*, *Introduction to the Practice of Fishery Science*, and *Fishery Development*. A fellow of the American Association for the Advancement of Science and of the American Institute of Fishery Research Biologists, he has been a member of the American Fisheries Society since 1935 and was elected to honorary membership in 1983.



Thomas R. Schroeder

Schroeder has worked almost his entire adult life managing fisheries in Alaska. He received his bachelor's degree in fisheries science from Colorado State University in 1967, and wrote a thesis on toxicity of pesticides and herbicides to salmon and trout while working on a master's degree. He joined the Alaska Department of Fish and Game's Division of Commercial Fisheries in 1969 as an assistant area biologist in Bristol Bay. In 1974, he was promoted to area management biologist for Lower Cook Inlet, one of the areas affected by the *Exxon Valdez* spill, and managed salmon, herring, bottomfish and shellfish fisheries until retiring in April 1990. Following the spill, he walked the beaches of Prince William Sound and the Gulf of Alaska with other state officials to examine the extent of oiling. A member of the American Fisheries Society since 1965, he is now a private fisheries consultant based in Homer, Alaska.



A.A. "Ole" Olsen

Olsen, a fisheries consultant in Anchorage, is a native Alaskan born in the small coastal village of Afognak, which was destroyed by a tidal wave in 1964. He worked on his family's fishing boats before launching an eight-year career as a bush pilot and salmon spotter flying throughout the state. In 1977, he entered the seafood processing industry as the manager of a salmon cannery and spent 10 years as an executive for firms packing fresh, frozen and canned salmon, crab and other fish for sale throughout the world. Following the spill, he was retained by Exxon as a consultant on commercial fisheries programs and as a liaison to villages of Alaskans whose diet consists largely of the fish and game they catch. He studied engineering and business for two years at the University of Portland, Oregon, and business for three years at the University of Alaska at Fairbanks.



William J. Allender

Over the past 15 years, Allender has worked in Alaskan canneries, on a hatchery construction crew and in several commercial fishing operations. For almost 10 years, he earned his living diving for herring roe in kelp beds and fishing for salmon, herring and bottomfish, with much of his experience in the area affected by the oil spill. Since 1988, he has operated Marcor Charters, a sports fishing business out of Cordova. A native of Big Fork, Minnesota, he is a Coast Guard-licensed captain for carrying passengers and cargo. Following the 1989 oil spill, he worked for 160 days on animal-rescue and eagle-capture teams. In 1990, as a consultant to Exxon, he traversed the beaches and waters of Prince William Sound and the Gulf of Alaska to help state officials ensure the safe operation of fisheries in the region.



Alaskan Fisheries — Two Years After the Spill



*A summary of findings
from the report of
William F. Royce, Ph.D.
Thomas R. Schroeder
A.A. "Ole" Olsen
William J. Allender*

February 1991

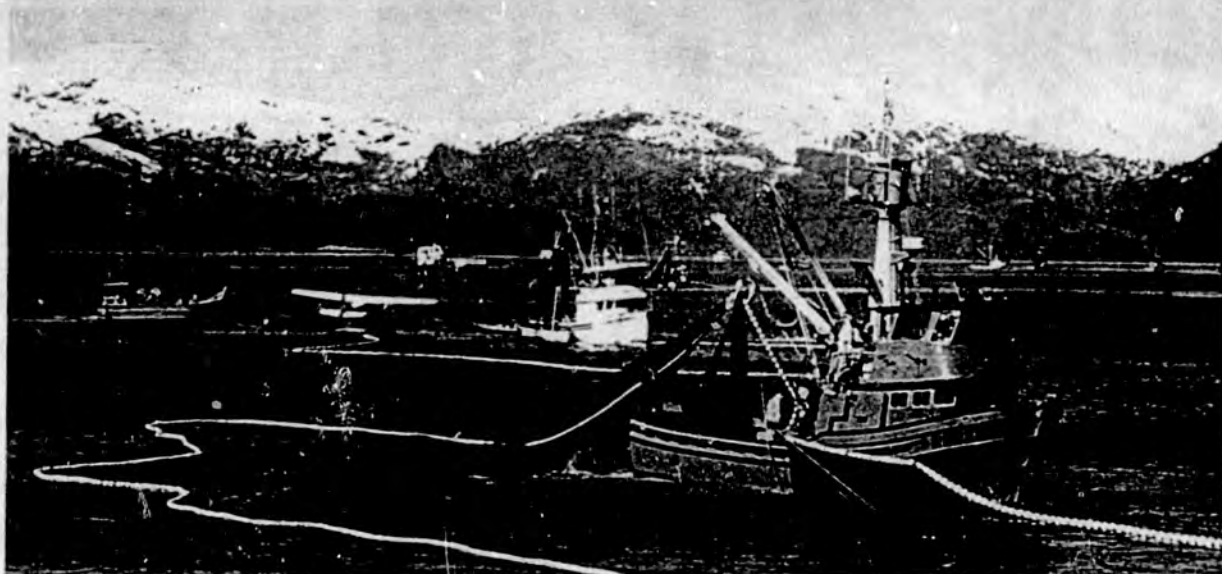
The Robust Fisheries of Prince William Sound, Alaska

Following the Exxon Valdez spill in March 1989, the authors were asked to address concerns about the potential effects of the spill on Alaska's fisheries.

Record 1990 harvests. Fishermen in Prince William Sound enjoyed record-breaking commercial catches during 1990. In April, purse seiners netted 8,300 tons of herring — more than the entire year's harvest quota — in only 20 minutes, though the season typically lasts several hours. Then, over the summer, fishermen caught 44.2 million pink salmon in the Sound, far eclipsing the previous record of 29.2 million fish.

Significant salmon harvest. The enormous pink salmon catch was especially significant because these two-year-old adults had traveled through Prince William Sound's waters as vulnerable fry in the months following the spill. Because the pink salmon proved so resilient, the other, less vulnerable salmon species should have prospered as well.

Abundant herring. Since herring spawn in shallow waters, there was potential in 1989 for these spawning fish to become exposed to oil. The 1990 harvest of 8,300 tons, 32% higher than the pre-season harvest quota, points to an abundance of these fish.



Fishermen netted 8,300 tons of herring — more than the entire year's harvest quota — in just 20 minutes last year.

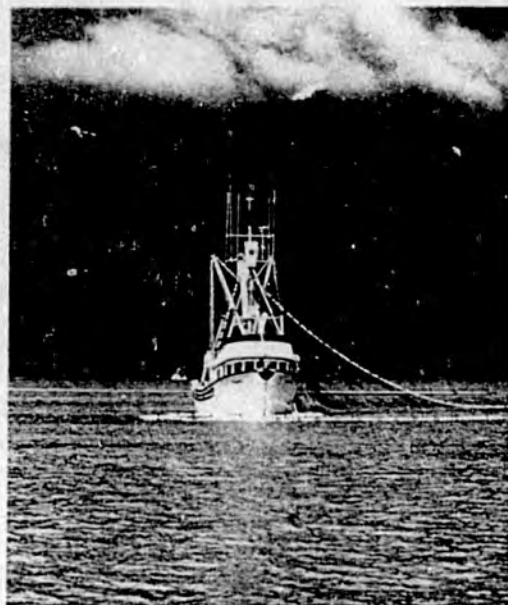
Statewide trend continues upward.

Despite the localized fishery closings in 1989, Alaska's statewide commercial fisheries production totaled \$1.3 billion, second highest ever. Although final figures are not available, preliminary reports indicate that the 1990 statewide salmon catch may surpass the 1989 totals, largely because of extraordinary returns in Prince William Sound. In addition, throughout 1989 and 1990 there were no confirmed reports of tainting or contamination from the spill.

Fishermen compensated for losses, hired for cleanup.

The area's commercial fishermen received financial compensation based on losses resulting from the various fishery closures in 1989. As of year-end 1990, Exxon had paid \$169 million to local fishermen in response to 1989 claims, and another \$133 million had been committed to fish processors and other related industries.

Exxon hired more than 10,000 people for the cleanup. Local fishermen proved invaluable to cleanup operations and wildlife-rescue programs with their knowledge of this remote area. 1,440 individuals and firms who had received compensation for



1990's pink salmon harvest of 44.2 million fish eclipsed the previous record of 29.2 million.

damages, including 1,160 local fishermen, were also paid more than \$105 million in wages and vessel-chartering fees.

Favorable long-term outlook. The potential long-term impact of the spill on fish is under careful study, but it is highly unlikely that any adverse effects on finfish populations will be discovered. In studies of earlier oil spills throughout the world—many of which were larger than the 1989 spill—no long-term damage has been documented. Based on recent fish catches in previously oiled areas, the outlook for commercial fishing is a positive one.

Some Important Questions and Answers

What might explain 1990's extraordinary Prince William Sound pink salmon and herring catches?

There was an unusually abundant plankton bloom in 1989, the largest on record, and this provided an extraordinary amount of food for the pink salmon that were harvested in 1990. The pink salmon harvest reflects the long-term trend of larger catches brought about by increased hatchery releases and a history of good management under the direction of the Alaska Department of Fish and Game.

The herring harvest of 1990 included fish that would have been caught in 1989 when the Prince William Sound herring fishery was closed.

Your report concentrates on pink salmon and herring. What about other species of fish?

These two species were chosen because they are important commercially and because they have implications for other species. The record catches of pink salmon and herring are significant because their primary spawning areas are located in

shallow intertidal areas that were in close proximity to the spilled oil, and because herring and pink salmon fry swam in the waters of the Sound soon after the spill.

Will the pink salmon and herring harvest levels in 1991 be related to the spill?

In view of the outstanding harvests of pink salmon and herring in 1990, there is no basis to expect any spill-related impacts in future harvests. Fish-harvest predictions are about as reliable as long-range weather forecasts; nature is very unpredictable.

Do hydrocarbons accumulate in fish?

No. Hydrocarbons are not like DDT or other toxins which accumulate through the food chain. Fish have the capacity to metabolize, or naturally break down, hydrocarbons and expel them from their systems.

Are some Alaska fish normally exposed to hydrocarbons?

Yes. There are 29 known naturally occurring oil seeps along the Alaska coast, and there has never been any indication that this constant source of petroleum has harmed a fishery.



The Authors



William F. Royce, Ph.D.

Professor Emeritus of Fisheries in the College of Ocean and Fishery Sciences of the University of Washington in Seattle and retired executive of the U.S. National Marine Fisheries Service. For many years, Dr. Royce has studied fisheries management and the fish species of Alaska.



Thomas R. Schroeder

A fisheries consultant based in Homer, Alaska. He recently retired from the Alaska Department of Fish and Game, where he served as commercial fisheries management biologist for part of the area affected by the oil spill.



A.A. "Ole" Olsen

An Anchorage fisheries consultant and former fisherman, bush pilot and manager of seafood processing plants throughout Alaska. In 1989 and 1990, he reviewed results of scientific tests of the area's fish stocks with Alaskan villagers who rely on seafood for subsistence. He also participated in 1990 fishery related spill cleanup activities.

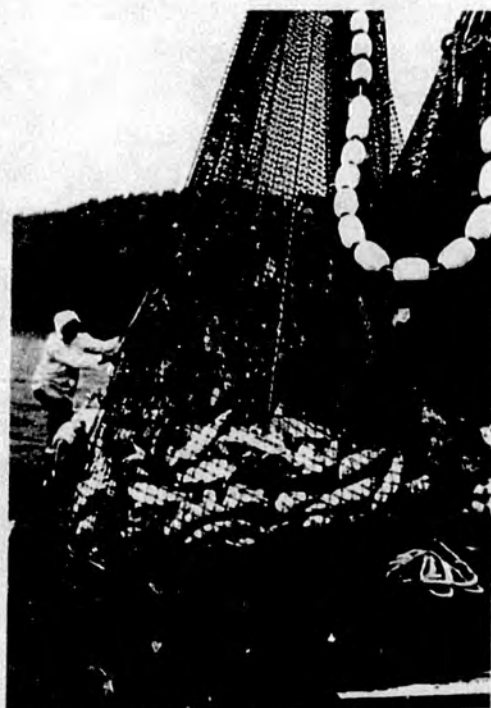


William J. Allender

A former commercial fisherman and owner/operator of a sport fishing business based in Cordova Harbor in Prince William Sound. In 1990, as a consultant to Exxon, he worked with the Alaska Department of Fish and Game to help ensure the safe operation of Prince William Sound fisheries.

If you are interested in more details about the Prince William Sound fisheries or wish to receive a copy of the full report, "Alaskan Fisheries — Two Years After the Oil Spill," please write to:

Cook Inlet Fisheries Consultants
P.O. Box 636
Homer, Alaska 99603



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DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Food and Drug Administration
Washington DC 20204

AUG 21 1990

Thomas S. Nighswander, M.D., MPH
Chairman, Alaska Oil Spill Task Force
Alaska Native Medical Center
255 Gambell Street
Anchorage, Alaska 99501

Dear Dr. Nighswander:

I am pleased to send you the enclosed FDA advisory opinion on the safety of aromatic hydrocarbon residues found in subsistence foods that were affected by the Exxon Valdez Oil Spill.

We hope that this advisory and its accompanying report by the Center for Food Safety and Applied Nutrition's (CFSAN) Quantitative Risk Assessment Committee (QRAC) will provide the necessary safety guidelines for timely interpretation of the data. I wish to emphasize that these are guidelines only. The advisory is not an official FDA action level. It is not a national advisory and it pertains only to the very special conditions having to do with the Exxon Valdez Oil Spill.

Sincerely yours,

Fred R. Shank, Ph.D.
Director
Center for Food Safety
and Applied Nutrition

Enclosure:

August 9, 1990

REPORT OF THE QUANTITATIVE RISK ASSESSMENT COMMITTEE

Subject: Estimation of Risk Associated with Consumption of Oil-contaminated Fish and Shellfish by Alaskan Subsistence Fishermen Using a Benzo[a]pyrene Equivalency Approach

INTRODUCTION

In this report, QRAC is responding to a request to the FDA Commissioner by the Alaska Oil Spill Health Task Force. This Task Force is an inter-agency advisory group on the effects of the oil spill on health and human resources. The members of the task force include the following organizations or agencies: The North Pacific Rim; the Kodiak Area Native Association; the Alaska Area Native Health Service; Exxon Company, U.S.A.; the State of Alaska Department of Health and Social Services; the State of Alaska Department of Fish and Game, Subsistence Division; the State of Alaska Department of Environmental Conservation, Division of Environmental Health. The Task Force has been charged with providing guidance for the sampling studies of subsistence foods that were affected by the Exxon Valdez Oil Spill and in interpreting the results of these studies to the public. Lack of safety guidelines for aromatic hydrocarbon contamination in foods, particularly seafood, has hampered the Task Force's work; hence the request to the FDA.

Two surveys of fish consumption were submitted to the agency. One report surveyed the fish consumption patterns of the village of Chenega Bay (population 60) on Evans Island in Prince William Sound and was conducted by the Alaska Department of Fish and Game, Division of Subsistence in 1984 and 1986. This survey is particularly appropriate for QRAC's purposes since this is an area where fish and shellfish were recently exposed to oil after the EXXON VALDEZ incident. In a second report, food consumption on Kodiak Island, Alaska, was surveyed by the Kodiak Area Native Association and the State of Alaska in 1983.

USE OF THE EQUIVALENCY APPROACH IN ESTIMATING RISK ASSOCIATED WITH POLYCYCLIC AROMATIC HYDROCARBON (PAH) CONTENT

The equivalency approach for PAH has been discussed in a memorandum to the QRAC (Memorandum, C. Carrington, Ph.D., Standards and Monitoring Branch (HFF-156) to S. Henry, Ph.D., (QRAC) dated June 26, 1990). The equivalency approach is a technique for assessing the risk from a number of different

compounds that are present in a single exposure source. Instead of calculating individual risks for each component, one component of known potency is used as a standard and the concentration of each of the other components is adjusted on the basis of its estimated, comparative potency to calculate a concentration equivalent to the standard. Summation of the equivalent concentrations produces a single number from which the risk may be estimated.

Two rationales for using the equivalency approach in the case of a risk assessment for PAH are applicable. First, there may not be fully adequate data for assessing risk for all of the individual components of the mixture, nor is it feasible to obtain such data. However, there may be data from in vitro systems or short term in vivo exposures that measure a parameter thought to be relevant to the carcinogenic mechanism of the compounds that allows the potency of a data-deficient component to be quantitatively related to a compound for which a long-term study is available. Second, the data available for estimating risk may be much better for some of the components than others. In such cases the potencies of the components for which there are relatively little data are highly subject to revision, whereas the potency number for a well studied compound may be expected to be stable. Calculation of an acceptable intake based on the concentration of the component with the best available data will be the least likely to require revision.

The risk calculated by this procedure is only an estimate. It is invariably more reasonable than the estimates obtained either by ignoring all but a few well described contaminants or than by assuming that all the congeners have equivalent potencies. The available toxicology data for benzo[a]pyrene (B[a]P) are much better than those data available for any of the other compounds detected in the fish. Short-term studies for most of the compounds are available that allow potencies relative to B[a]P to be approximated. These studies include (a) comparison of the initiating potency of individual PAHs after a single dermal application, followed by promotion; (b) comparison of the carcinogenic potency of individual PAHs after intraperitoneal injection in dimethyl sulfoxide in new born CD-1 and Swiss Webster mice; (c) comparison of the carcinogenic effects after implantation in the lungs of female Osborne-Mendel rats; (d) comparison of the carcinogenic potency of individual PAHs after long-term dermal application (National Institute of Public Health and Environmental Protection of the Netherlands, 1989; ICF-Clements Associates, 1990). Therefore, the equivalency approach is desirable in that it will emphasize the

data considered to be the most sound and facilitate the incorporation of anticipated future revisions in the relative potencies of the PAHs other than B[a]P.

ESTIMATION OF THE BENZO[a]PYRENE EQUIVALENTS (B[a]PE)
OF OTHER PAHS

Two recent documents have dealt with the relative potency of polycyclic aromatic hydrocarbons (PAHs), one produced by the National Institute of Public Health and Environmental Protection of the Netherlands (1989) and the other produced by Clement Associates (1990) under a contract with the EPA. Both reports review a total of 19 studies with 5 common to both documents. The Netherlands report used a linear model for calculating potency, while the EPA report used either a two-stage (Moolgavkar and Knudson, 1981) or a linear multi-stage model. The potencies from neither report are entirely suitable for QRAC's purposes. However, because the Clements report provided estimates for more of the compounds in question and because it systematically selected the best study for each compound, the analysis below used the equivalencies derived with the multistage model. This model more closely resembles the risk estimate procedure typically used by the QRAC than does the two-stage model.

The Clements report did not provide multistage estimates for either pyrene or fluoranthene. However, the best available study was selected for pyrene (Wislocki et al., 1986). Fluoranthene was not considered in the Clements report. The one study listed in the Dutch report in which a clear tumorigenic response was observed was therefore used to calculate a potency number for fluoranthene (Busby et al., 1984).

Table 1 lists the potency numbers relative to B[a]P judged to be the best available for the nine polycyclic aromatic hydrocarbons measured in the Alaskan marine samples. The B[a]PE values are positively correlated with carcinogenic potency. For the purposes of B[a]P equivalency, all the compounds in the Table are assumed to be probable human carcinogens, despite the conservatism in this approach implied by the IARC Classification.

Table 1. B[A]P EQUIVALENCIES FOR NINE PAHS

PAH	B[a]P equivalency	IARC Class *
Fluoranthene ^b	0.02	3
Pyrene ^b	0.13	3
Benz[a]anthracene	0.014	2A
Chrysene	0.013	3
Benzo[b]fluoranthene	0.11	2B
Benzo[k]fluoranthene	0.07	2B
Benzo[a]pyrene	1.00	2A
Indeno[1,2,3-cd]pyrene	0.25	2B
Dibenz[a,h]anthracene	1.05	2A
Benzo[g,h,i]perylene	0.03	3

* IARC classification: 2A - probable human carcinogen; 2B - possible human carcinogen; 3 - unclassifiable.

^b All values are from Clements Associates except for pyrene and fluoranthene which were calculated by Janet Springer (Memorandum, J. Springer, Division of Mathematics (HFF-110) to C. Carrington, Ph.D., (HFF-156), dated June 19, 1990).

For the alkylated PAHs, the addition of the side chains was assumed to have no effect on carcinogenic potency. Since the alkylated compounds were reported as either mixtures of fluoranthenes and pyrenes or chrysenes and benz[a]anthracenes, the assumption was made that the relative proportions of the alkylated mixtures was the same as the unsubstituted compounds which were measured separately. The alkylated PAHs were not placed in any IARC category since there are no data.

LEVELS OF BENZO[a]PYRENE EQUIVALENTS IN ALASKAN FISH AND SHELLFISH SAMPLES

The spreading of oil spilled from the EXXON VALDEZ (March 24, 1989) led to concern among native Alaskans that their seafood could be contaminated by petroleum hydrocarbons. In response, the National Oceanic and Atmospheric Administration (NOAA) entered into a memorandum of understanding with Exxon to analyze several hundred subsistence fish and shellfish from 13 subsistence fishing grounds used by native Alaskans in or near Prince William Sound for aromatic contaminants which included aromatic hydrocarbons and dibenzothiophenes. Uncontaminated fish and shellfish samples were collected near the village of Angoon in southeast Alaska to serve as a reference. Results of analyses of samples collected from July through September 1989 are reflected in this QRAC report as taken from a NOAA report (Varanasi, 1990).

The NOAA study indicated that the pattern of aromatic contaminants in the fish samples is consistent with the known extensive metabolism of aromatic hydrocarbons by fish. In molluscs, which have little ability to metabolize aromatic contaminants, both alkylated and unsubstituted aromatic contaminants were present.

Using the equivalency values in Table 1., the B[a]P equivalencies in the Alaskan fish and shellfish samples are shown in Table 2.

6

Table 2. B[a]P EQUIVALENCIES (ppb) IN THE ALASKAN FISH AND SHELLFISH SAMPLES

Source	Number of Samples Analyzed					
	ppb	<0.5	1	2-5	8-17	>49
Fish (incl. salmon)	>100	0	0	0	0	0
Molluscan bivalves (except WB)	139	11	4	1	0	
Windy Bay molluscan bivalves	1	0	2	2	2	
Smoked salmon	0	0	0	0	0	4

Individual values (ppb) for Windy Bay molluscan bivalves and smoked salmon:

Windy Bay molluscan bivalves: 0, 3, 4, 11, 17, 71, 107 Mean = 30

Smoked salmon: 49, 52, 133, 215, Mean = 112

In Table 2, it may be seen that levels of B[a]PE are higher in the smoked salmon. PAHs in smoked foods are known to be generated by pyrolysis of the smoke constituents during preparation; searing or smoking food commonly results in a considerable increase in PAH levels (Fazio and Howard, 1983).

FISH CONSUMPTION ESTIMATE FOR ALASKAN SUBSISTENCE FISHERMEN

The Food and Color Additives Review Section (FCARS) (memorandum M.A. Adams, Ph.D., HFF-415 to Mike Bolger, Ph.D., Contaminants Team, HFF-156) has evaluated for QRAC the two Alaskan subsistence fish consumption surveys previously mentioned.

Fish consumption patterns were surveyed for the village of Chenega Bay on Evans Island, Prince William Sound by the Alaska Department of Fish and Game, Division of Subsistence between 1984 and 1986 (Alaska Dept. of Fish and Game). Chenega Bay is

accessible only by air or water. The residents, 77% of whom are Alaska Native, use traditional hunting and fishing practices to obtain a major portion of their food.

Food consumption on Kodiak Island, Alaska, was surveyed by the Kodiak Area Native Association and the State of Alaska in 1983 (Kodiak Island Native Association, 1983).

FCARS also recently estimated freshwater fish consumption among subsistence fishermen in the contiguous United States. (Memorandum G. Cramer, Ph.D. (HFF-415) to S. Henry, Ph.D. (HFF-156), dated Nov. 13, 1989.) Consumption estimates from these three sources are tabulated for comparison in Table 3.

The residents of Chenega Bay are more dependent on food obtained directly from nature than are subsistence fishermen of the contiguous United States who have access to alternate food sources such as supermarkets or farms. In addition, the rigors of living in a cold climate may increase the caloric demand of the body, requiring a higher food intake to maintain normal body function. Thus, it is not surprising that total per capita fish consumption is higher among the Alaskans than subsistence fishermen in the contiguous United States. Fish/shellfish consumption in the isolated Alaskan communities depends on resources available, prevailing customs and tradition, and access to alternate food sources from outside the community. Average fish/shellfish consumption values may vary somewhat from community to community, but all are of the same order of magnitude, as is illustrated by the Kodiak Island study when compared to the Chenega Bay study. Isolated Kodiak Islanders apparently make much greater use of the naturally occurring food resources.

8

Tabel 3. FISH AND SHELLFISH CONSUMPTION FOR SUBSISTENCE FISHERMEN
ALASKA AND CONTIGUOUS UNITED STATES

Resource	g/person/day
Chenega Bay survey (per capita data)	
Salmon ^a	89
All other fish ^b	52
Subtotal	141
Bivalve mollusks ^c	2
Crabs ^d	.8
Shrimp	11
Subtotal	21
Kodiak Island Alaska (per capita data)	
Most isolated population	
Fish (excl. shellfish)	369
Butter clams	27
Less isolated population	
Fish (excl. shellfish) ^e	124
Butter clams	10
Contiguous United States (Estimate for subsistence fisherman & family - FDA)	
Freshwater fish	69 (mean) 116 (90th percentile)

^a Includes king, red, pink chum, and silver salmon.

^b Includes halibut, herring and herring roe, gray and black cod, red and black rockfish, smelt/eulachon, shark, eel, Dolly Varden, and trout.

^c Includes razor and other clam species, cockles, and mussels.

^d Includes dungeness, king and tanner crabs.

^e Mostly red and pink salmon.

RISK ASSESSMENT FOR CANCER

An approach to estimating the carcinogenic risk from contamination of food with many polycyclic aromatic hydrocarbons (PAHs) is to design a scheme whereby the total PAH contamination is expressed as benzo[a]pyrene potency equivalents. This approach has been taken above with the levels of PAHs found in the Alaskan fish/shellfish samples.

After evaluating the available data, the Cancer Assessment Committee of the Center for Food Safety and Applied Nutrition (CFSAN) concluded that the most suitable chronic cancer bioassay for B[a]P, although less than ideal, is the one reported by Brune et al. in 1981. In this study, there was one dose group of rats which were administered benzo(a)pyrene alone for their lifetime, a feature which was not available in the small number of other studies that might even be considered for this purpose. The fact that there is only one dosage level administered makes a dose-response evaluation somewhat limited. However, the existence of a low incidence of treatment-related tumors which were mostly benign, indicates that the response is at the lower end of the observable dose-response curve. The response, therefore, is where QRAC would initiate a linear extrapolation to a zero dose, even if there were more data points.

The administered dose in this study was 0.15 mg/kg bw/day, 5 days per week to Sprague-Dawley rats for 131 weeks. The males were more sensitive with 8/32 having either a benign forestomach tumor or esophageal tumor. The control group had an incidence of rats with benign forestomach tumors of 2/32 after 129 weeks. The time-averaged daily dose was:

$$0.15 \text{ mg/kg bw/day} \times 5/7 = 0.107 \text{ mg/kg/bw/day}$$

UNIT RISK (potency)

$$\frac{8/32 - 2/32}{0.107 \text{ mg/kg bw/day}} = 1.75 \text{ (mg/kgbw/day)}^{-1}$$

QRAC has chosen to use the Chenega Bay fish/shellfish data as presented in Table 3 for the estimation of upper bound lifetime risks presented in Table 4. It is believed that the Chenega Bay residents are among the most likely consumers of fish/shellfish that might have come in contact with spilled oil, making the Chenega Bay data most useful and relevant for risk assessment.

Table 4. RISK FOR ALASKAN SUBSISTENCE FISHERMEN CONSUMING PAH-CONTAMINATED FISH AND SHELLFISH

Source	Intake ^c (g/p/day)	B[a]PE ^a (mg/p/d)	Upper Bound Lifetime Risk ^b
Salmon ^d	89	ND ^e	NQ ^e
All other fish ^d	52	ND ^e	NQ ^e
Smoked Salmon ^f	45	5.0×10^{-3}	1.5×10^{-4}
Bivalve mollusks ^g	2	6.0×10^{-5}	1.8×10^{-6} ^h

^a From Table 2, the mean concentration of B[a]PE for smoked salmon is 112 ppb B[a]PE $\times$ 44.5 g = 5.0×10^{-3} mg/p/d.

^b For Smoked Salmon:

$$\frac{5.0 \times 10^{-3}}{60 \text{ kg person}} \text{ B[a]PE} \times \text{unit risk of } 1.75 = 1.5 \times 10^{-4}$$

^c Taken from Table 3

^d Includes halibut, herring and herring roe, gray and black cod, red and black rockfish, smelt/eulachon, shark, eel, Dolly Varden, and trout. Salmon is mostly red and pink salmon.

^e ND - not detectable; NQ - not quantifiable.

^f Alaskan subsistence fishermen are estimated to consume about 50% of their salmon catch smoked. (Personal communication, Dr. Robert Wolfe, Director, Div. of Subsistence, Alaskan Dept. of Fish and Game, Juneau, Alaska.)

^g Using the mean Windy Bay value of 30 ppb for molluscan bivalves from Table 3.

^h This assumes that persons are exposed to B[a]PE for their entire lifetime from this oil spill. It can be assumed that exposure would be at most no more than 10 years at this level. Therefore, at a minimum, the upper bound lifetime risk can be adjusted by a factor of 1/7 of a lifetime (i.e., $1/7 \times 70$ years = 10 years) to provide an adjusted upper bound risk of 2.5×10^{-7} .

The dose corresponding to a 10^{-6} lifetime upper bound risk would be:

$$10^{-6} / 1.75 \text{ (mg/kg bw/d)}^{-1} = \underline{0.57 \text{ ng/kg bw/d}}$$

For a 60 kg person, the dose corresponding to a 10^{-6} lifetime upper bound risk would be:

$$0.57 \text{ ng/kg bw/d} \times 60 \text{ kg person} = \underline{34 \text{ ng B[a]PE/person/day}}$$

For the purpose of estimating levels of concern for B[a]PE from the Exxon Valdez oil spill in subsistence fishery resources it will be assumed that the impact of the spill will occur for no more than 10 years. This assumption is based on data accumulated from prior spills where the environmental status of an impacted area generally returns to that which existed prior to the spill within several years. The evidence from these spills indicates that oiled environments do cleanse themselves and that there are environmental mechanisms of oil degradation and biological recovery (National Research Council, 1985). Therefore, the duration of exposure would not be for a 70 year life-time, but rather for 10 years or less. The following table presents advisory levels for various subsistence fishery resources.

TABLE 5. FDA ADVISORY LEVELS FOR ALASKAN SUBSISTENCE FISHERY RESOURCES

Resource	Intake g/person/day	B[a]PE Levels for 10^{-6} Risk (ppb)	
		<u>Lifetime</u>	<u>10 year</u> ^a
Salmon	89	0.4	3
Other finfish	52	0.7	5
Bivalve mollusks	2	17.0	120
Crustaceans	21	1.6	11

^a Advisory level corresponding to a 10^{-6} risk and a period of exposure of 10 years (1/7 of a lifetime of 70 years):

$$\text{Advisory Level} = \frac{34 \text{ ng B[a]PE/person/day}}{\text{g of fishery resource/person/day}} \times 7$$

(ppb or ng/g)

where: 34 ng B[a]PE = dose corresponding to a 10^{-6} lifetime upper bound risk

7 = correction factor for less than lifetime exposure of ten years

If a 10^{-5} upper bound risk standard were used rather than a 10^{-6} upper bound standard, then the corresponding advisory levels would be 10-fold greater than those presented in Table 5. In the case of the dioxin advisory opinion a 10^{-6} upper bound risk standard was used. Other governmental institutions (e.g. Environmental Protection Agency and various states) have often based their risk assessment decisions on a 10^{-5} risk standard. The issue of an acceptable risk standard for a consideration like subsistence fishing is one that resides with the state.

These advisory levels can be interpreted as concentrations which if not exceeded for the given conditions of exposure (lifetime or 10 years consumption at 7-fold higher levels) will conservatively limit any carcinogenic risk from ingested B(a)PE to less than 10^{-6} . The actual risk may be lower than these figures suggest. Although PAHs produced by smoking fish are unrelated to the oil spill, an advisory level of 0.8 ppb could be established for smoked salmon (0.8 ppb = 34 ng B(a)PE/45 g salmon). Since the mean concentration of B(a)PE in smoked salmon was reported to be 112 ppb (see Table 2), this illustrates the importance of this method of food preparation as a source of PAHs.

Generally the procedures used to estimate low levels of carcinogenic risk provide exposure levels which are well below those which elicit other toxicological end-points. Therefore, any advisory level based on carcinogenic activity of a toxicant is an conservative estimate of risk which would virtually always subsume the risk from other potential toxicological endpoints.

CONCLUSIONS

The PAHs reported in the subsistence survey account for the majority of the aromatic residues that are measurable by current available analytical methodology. The risk assessment is therefore confined to these measurable PAHs.

In interpreting the risk estimates and advisory levels presented in Tables 4 and 5, several points should be emphasized. First, the equivalency approach to estimating the potencies of various PAHs taken in this report is based on several assumptions pointed out earlier. This approach cannot be assumed to produce exact potencies for the PAHs. Second, there are limitations in the laboratory animal data used to estimate the potency of B(a)P and other PAHs. Third, as with all QRA quantitative risk assessments, an upper bound risk estimate has been produced with the knowledge that the true risk is somewhere between the upper bound number presented and zero.

With regard to fresh salmon, the dose level corresponding to the lifetime 10^{-6} upper bound risk level is at or below the detection limit of the PAHs. The risk associated with the consumption of salmon which is not smoked is insignificant relative to that associated with consuming smoked salmon because smoking significantly increases the PAH level.

Analyses of molluscan bivalves from areas unaffected by the oil spill have indicated that PAH levels are negligible (Varanasi et al., 1990). The risk estimate presented for molluscan bivalves in Table 4 is predicated on the conservative assumption that persons at risk would consume molluscan bivalves contaminated at the level of PAH produced by the Exxon Valdez oil spill for a lifetime; molluscan bivalves would not be expected to be contaminated with PAHs at this level for such a long time period.

Therefore, QRAC concludes that the lifetime upper bound risk of consumption is low for unsmoked salmon, other finfish, crustaceans, and oil-contaminated molluscan bivalves.

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**Advances in Rehabilitating
Oiled Sea Otters:
The Valdez Experience**

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Summary

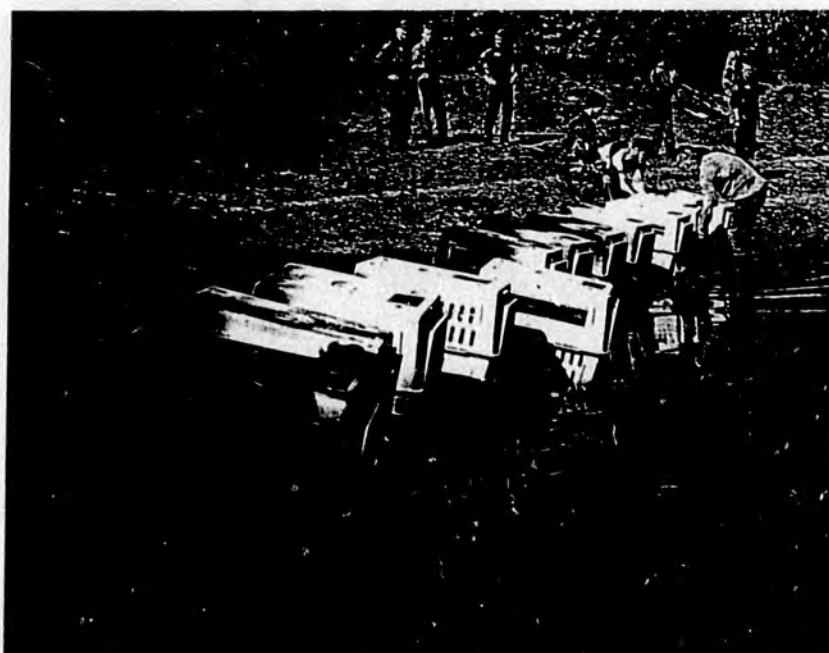
The March 1989 Valdez accident was the first oil spill to involve large numbers of sea otters. Similarly, the response to the Valdez spill involved the largest effort ever to rescue and rehabilitate oiled sea otters. Volunteers and employees captured and delivered 357 otters to the Sea Otter Rehabilitation Centers following the spill. While many of these animals regrettably died, the majority (197) were eventually returned to the wild. Another 37 were placed with seaquariums.

The Sea Otter Rehabilitation Program demonstrated that large numbers of oiled sea otters could be successfully rehabilitated following an oil spill. The experience was often painful and always trying, but it nonetheless contributed enormously to the wildlife rehabilitation community's understanding of what is needed to successfully rescue and treat sea otters after an oil spill. This paper describes some of the ground-breaking developments concerning sea otter rehabilitation. It focuses on rehabilitation facilities, staffing, and the collection of scientifically valuable data.

Background

Although at least 28 oil spills have been larger than Valdez, the March 1989 accident represents the first oil spill to affect a large number of sea otters. More than 16,000 sea otters inhabited the portions of Prince William Sound and the Gulf of Alaska that were impacted by oil (Degange, 1990). This would mean that many of the area's estimated 45,000 sea otters (Townsend, 1989) might have been involved.

At the request of the U.S. Department of the Interior and the U.S. Fish and Wildlife Service (USFWS), Exxon Company USA initiated an unprecedented effort to rescue and treat sea otters that became oiled. They built rehabilitation and pre-release facilities in Valdez, Seward, and Homer—each with a capacity of about 100 otters. All the facilities remained in operation until September, 1989. At its peak, the sea otter rehabilitation program had over 350 paid and volunteer staff, 11 capture vessels, and a dedicated helicopter to transport otters from the capture boats to the rehabilitation centers.



Following the largest effort ever to rescue and rehabilitate marine mammals, 197 sea otters were returned to the wild.

McCloskey, J. Stewart, T.D. Williams, and G. Van Blaricom.

Primary Rehabilitation Facility

The primary rehabilitation facilities in Alaska quickly evolved into a flow-through system with several specialized areas. Sea otters could be moved in assembly-line fashion through areas for triage and sedation, cleaning and rinsing, drying, recovery from sedation, critical care, and pens with seawater pools for short-term holding. Sea otter pups require constant attention and should receive care in a separate nursery area. A kitchen is also needed to prepare the large amounts of seafood that sea otters require to maintain their normally high metabolic rate.

In Appendix 1, the space needs and possible configuration for a flow-through primary facility are described. This sample design would allow simultaneous treatment of 200 otters, with holding pens for 120 otters and space in large pools for another 80. This size was selected because it matches the total capacity of Exxon's two sea otter rehabilitation centers and should be adequate for most moderate-to-large oil spills when combined with a pre-release (i.e., post-treatment) facility (details below). The total number of animals that could be moved through this primary facility to the pre-release facility depends on the rate of rehabilitation. The indoor space measures about 80 ft x 275 ft while the outdoor holding area measures 60 ft x 250 ft.

Because large pools and a filtered seawater system are needed for holding sea otters, the primary rehabilitation facility needs to be a permanent structure. Even with detailed plans and the identification of sites with essential amenities, it may take several weeks to build an otter rehabilitation center. To enable a rapid response that would minimize the exposure of otters to crude oil and reduce mortality, policy-makers would need to consider the development of pre-existing facilities. The more

rapid the response, the more effective future rehabilitation efforts can be.

Triage and Sedation

The area for triage and sedation should be designed and stocked to meet the medical and hygienic needs of the in-coming otters. When oiled sea otters first arrive at the rehabilitation center, they are brought to the triage room for initial examination, medical stabilization, weighing, and sedation prior to cleaning. The veterinary staff treats any immediate problems such as dehydration, hypothermia, hyperthermia and shock. The room should have a sink and cabinets that can be locked for storing drugs and other medical supplies. The floors should be covered with a non-porous surface that can be easily cleaned. The temperature should be controlled at 18° C (65°F).

When large numbers of otters might be captured more than 300 miles (a four hour helicopter flight) from the primary facility, a remote mobile triage unit would be beneficial. Such a facility is described in detail in Appendix 2.

Cleaning

Unlike pinnipeds and cetaceans—which have a subcutaneous layer of blubber—sea otters rely on their fur for thermal insulation in water. If otter fur



Specially designed pens allowed otters to groom naturally.

Portable/Transport Pens

After drying, the animal is placed in a portable cage in the recovery room while the effects of sedation wear off. Because otters that have been oiled and cleaned may have difficulty thermoregulating at ambient air temperatures (especially during the winter in northern latitudes), they should be kept in the recovery room until they are alert and begin grooming.

The specially designed cages (figure 2) used in the critical care facility has a slatted bottom to allow the passage of feces and urine, which helps keep the otter's fur clean. The walls are made of pliable netting that prevents injury to teeth and gums. The

sliding, plywood door on top allows easy access to the animal for physical examination and medical treatment. The cages are placed over a shallow trough in the floor that is coated with fiberglass. Feces and urine which fall into the trough are washed into drains that are connected to the sewer. This makes sanitation easier.

Holding Pens

After recovery from sedation, the otter should be taken to an outdoor holding pen with a small seawater pool where it can groom and feed (figure 3). To protect the animals from injury, cage frames should be made of polyvinylchloride pipe or other plastic material with rounded edges. Because otters

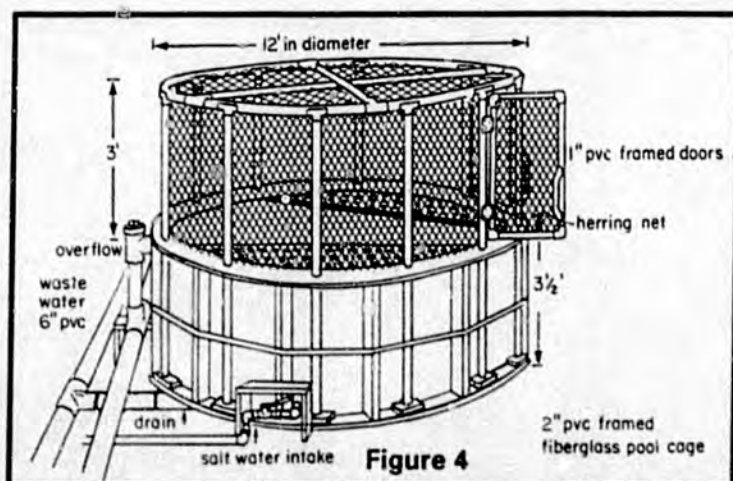
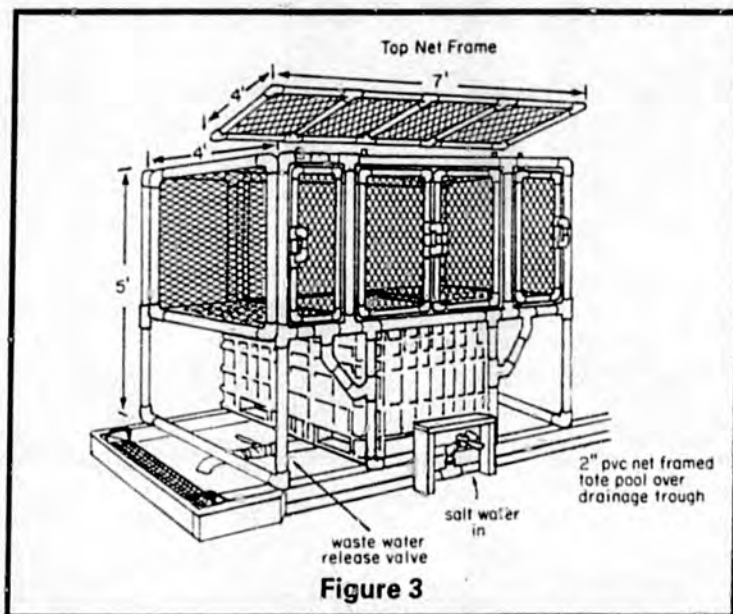
will attempt to chew away the cage lining, the framework of the pens should be covered with two-inch stretch-mesh herring net to prevent any injury to the otters' teeth and gums.

To encourage the grooming that is crucial for restoration of the fur, the pens should have pools that are at least three feet square and two feet deep. In addition, haul-out platforms (two feet by three feet) should be placed on either side of the pool. The surface of the haul-out platforms should be smooth but perforated with small holes to allow water to drain.

The pools should be plumbed with a continuous supply of filtered seawater to maintain good water quality and low bacterial concentrations. We found it advantageous to place the pens in a shallow spillway that collected overflowing seawater and returned it to the ocean. In areas where there might be a heavy snow fall, the outdoor pen area should be covered by a translucent, plastic roof.

Holding Pools

Once the recuperating otters have restored the water repellency of their fur and are in good health, they should be moved to larger pools that enable greater movement (figure 4). These pools can be any shape that allows the animals to socialize in larger groups and maintain muscle strength. We



with cleaning. As a result, mortality decreased dramatically, and more than 70% of the otters arriving at the rehabilitation centers after the third week survived.

Recognition of the two distinct phases of a crude oil spill should enable veterinarians and animal care specialists to anticipate the medical problems and prepare for them in future spills. In addition, new, more effective treatment protocols can be devised now that we better understand the clinical effects of crude oil on sea otters.

Pup Nursery

Successful techniques to raise sea otter pups have been perfected by the Monterey Bay Aquarium and Sea World. The nursery should occupy a separate room to create a quiet, low stress environment. The basic requirements include a small kitchen (sink and refrigerator) for preparing and storing formula, a second sink and counter top for washing and grooming the pups, and a waterbed on which the pups can rest and play. The unheated waterbed has been shown by animal care specialists at the Monterey Bay Aquarium to be beneficial for the successful rearing of young otter pups, possibly because it is pliable and simulates the surface of the ocean. Because sea otter pups require 24 hour care, we found it useful to place a cot in the room for the caretakers to use at night.

Husbandry Facilities

Throughout the rehabilitation process, the primary responsibility of the husbandry staff is to feed and monitor the otters in their pens. If a rehabilitation facility has 200 adult otters each weighing 20 kg and eating 25% of their body weight in food each day, then the kitchen staff must thaw 1000 kg of sea food daily. The food preparation kitchen should have at least 1000 cubic feet of freezer space for frozen seafood. This is enough space to store three to four days of frozen sea food for 200 sea otters. Ten stainless steel sinks (3 feet x 3 feet x 2 feet deep) are used to thaw the frozen food which is placed into plastic bags, weighed (one kilogram portions), placed in buckets with ice and distributed by the husbandry staff. Pre-weighing the food in plastic bags makes it easier for the husbandry staff to estimate the food consumption of each otter, at least while it is in one

of the holding pens. The waterproof floor and stainless steel counter tops should be sanitized at least once per day. For convenience, a commercial ice maker should be in or adjacent to the kitchen.

Other Facility Considerations

When choosing the site for a primary rehabilitation facility, additional requirements include all-weather access by road and aircraft, telephone communications, and easy access to fresh seawater and a commercial seafood supplier.

Although the primary function of the facility is to clean and rehabilitate oiled animals, the Valdez spill proved the wisdom of allocating space for administration, staff training, and public relations.

To ensure the health of the otters and the staff, coveralls should be issued to all persons to wear over their street clothing. A dressing room with small lockers to store personal belongings should be provided. Staff members should eat only in a designated lounge, which can also be used for training programs and staff meetings.

To prevent the introduction of domestic animal diseases into the wild population, quarantine procedures are essential in the rehabilitation centers. Transport cages should be cleaned and sanitized after use. All pets and unnecessary visitors should be excluded from the site. Ideally, visitors and press corps should be confined to an interpretative center or allowed to view the otters from behind a glass partition.

Pre-release Facilities

Normally about two weeks are required to rehabilitate an oiled sea otter, although the duration may be longer in cases of severe petroleum hydrocarbon toxicosis. Rehabilitated otters should be moved to seawater pens in a pre-release facility as soon as they satisfy the following criteria:

1. Fur is water repellent; otter is able to thermoregulate (does not become chilled) in water;
2. Otter exhibits regular grooming behavior; fur appears healthy and retains loft;
3. Otter is eating well; body weight is either stable or increasing;
4. Otter appears alert and socializes with pen mates;

easily obtained near developed areas. If a large preemptive capture effort is planned immediately after a spill, quick access to seawater pre-release pens would be vital. A modular system like the one above would allow rehabilitators to store and quickly assemble the pens when needed. A modular design also enables the addition of new pens as needed, thereby allowing unlimited capacity.

Staffing and Management Issues

To avoid misunderstandings and inefficiency, the management at a sea otter rehabilitation center requires well defined authority from the USFWS (the federal trustee for sea otters). The organization needs to be interactive and encourage the free exchange of information in order to improve operations, but staff members also need a clear understanding of the chain-of-command. A sample breakdown of job responsibilities is included as Appendix 3.

Otters require continuous care, so a core professional staff of administrators, veterinarians, veterinary technicians and animal care specialists is required. Volunteers can be a valuable supplement to the core professional staff if they are properly trained and supervised. Jobs that can be filled by volunteers include animal monitors, kitchen staff, and logistical support for the rehabilitation center (i.e., transportation of personnel and otters, radio and telephone communications, administrative support).

The total staff should be large enough to accommodate 12 hour shifts while providing 24 hour care for the animals. Some overlap in shifts will allow the exchange of information among staff members, especially among the husbandry staff. We learned that appropriate staff size is a function of the number and health status of otters in the facility. A ratio of one to three staff per otter (1/2 to 1 1/2 people per 12 hour shift) is usually adequate.

A training program for volunteers with yearly refresher courses needs to be an integral part of a pre-existing facility if one were built. This ensures that a group of knowledgeable and highly motivated volunteers could be immediately available if an emergency arises. Training programs for volunteers should include instruction on sea otter behavior, health effects of exposure to crude oil, common

veterinary procedures and their purposes, sanitation and hygiene in animal facilities, record keeping, and quarantine procedures for disease control. Following the Valdez oil spill, training videos were produced on some of these topics to accompany lectures for new staff members.

Data Collection and Analysis

Much valuable information was collected during the 1989 Sea Otter Rehabilitation Program in Alaska that will be used to develop new medical and husbandry protocols. The most useful information fell into five categories:

1. Sea otter biographical data
 - a. Date, location of capture, tag number
 - b. Body weight at time of capture
 - c. Degree of oiling and medical condition
 - d. Pregnancy and birth data
 - e. Final disposition
2. Medical treatments
 - a. Anesthetics
 - b. Antibiotics
 - c. Other drug therapies
3. Clinical laboratory results
 - a. Blood chemistry
 - b. Urinalysis
4. Food consumption
5. Necropsy results

For a detailed list of variables for each category of data, see appendix 4.

Preliminary analysis of the data have been published in a report entitled "Sea Otter Rehabilitation Program: 1989 Exxon Valdez Oil Spill" (Williams and Davis, 1990). Further analysis of the data is planned and should provide additional recommendations for the husbandry and veterinary care of oiled sea otters.

Science and wildlife rehabilitation will continue to benefit for some time from the quality of the Valdez data acquisition and analysis. This documentation process has proved worthwhile to help evaluate treatment protocols. In addition, this facilitates the sharing of information with other rehabilitation programs.

sue samples from most major organ systems were taken for histopathology and toxicology (petroleum hydrocarbon analysis). The analysis of polycyclic aromatic hydrocarbons and aliphatic hydrocarbons was directed by Dr. Terrie Williams and conducted at Battelle Ocean Sciences (Duxbury, MA). When evaluation of the results is completed, it may indicate which organ systems were most susceptible to damage from systemic exposure to oil. These data will be correlated with the types and concentrations of petroleum hydrocarbons in the tissues. In some sea otters, blood petroleum hydrocarbon levels were also measured (Williams, 1990). In acquiring a better understanding of the basis of petroleum hydrocarbons' effects on sea otters, we hope to improve veterinary protocols for oiled sea otters and thereby increase survivorship.

The third research project examined new techniques to restore the water repellency of sea otter fur after cleaning.

While the method for cleaning the fur of oiled otters worked well, the sea otters' fur did not fully regain its water repellency until several days after cleaning. As a result, cleaned otters could not be placed immediately into water because their fur wetted and they became chilled. Although the reasons for the delayed recovery of the water repellency of the fur are not known with certainty, possible explanations include: 1) the alignment of the dense underfur had been disrupted during washing so that it no longer trapped an air layer next to the skin; 2) the normally hydrophobic surface of the hairs retained a monolayer of detergent molecules which made their surface hydrophilic; and 3) washing had removed natural oils which normally contributed to the hydrophobic properties of the fur.

To discover if the time needed for fur restoration could be abbreviated, the rehabilitation centers invited Dr. Lee Hunter of Redkin Laboratories (Canoga Park, CA) to investigate the beneficial effects of applying squalene (an oil similar to the natural oils produced by the otter's sebaceous glands) to the fur of sea otters after they had been cleaned with Dawn™ dish washing detergent. Our hypothesis was that the application of squalene would replace the natural oils that are removed with crude oil during washing, thus returning the fur to its hydrophobic state. Squalene in ethanol was sprayed

on the fur of several otters after their fur had been washed and thoroughly dried. The water repellency of their fur was compared to otters in a control group which were not sprayed. The fur of the treated group appeared to dry quicker when the animals were out of the water. Although the results are preliminary, this research may result in a modified cleaning method, which will not only remove crude oil but will also restore the water repellency of fur immediately. Such a method could shorten the rehabilitation process by one to two weeks.

One problem that we had not anticipated in 1989 was how to decide when to stop capture operations. During the first few weeks of the spill, oil was visible on the fur of otters that were brought to the rehabilitation center in Valdez. However, as the oil dispersed and weathered, it became more difficult to decide when an otter was lightly oiled or unoiled. The situation was further complicated by the absence of information on safe levels of exposure to oil. As a result, the USFWS continued to capture sea otters in the oil affected area, probably longer than necessary.

In an attempt to provide more objective criteria for determining when otters should be brought to the rehabilitation centers, Dr. Ken Hill (staff veterinarian) developed a field test for detecting the presence of petroleum hydrocarbons on the fur of lightly oiled otters. This simple test involved placing a small hair sample from an otter in a 3 ml glass vial with dichloromethane (an organic solvent), which solubilized the oil and visually changed the color (clear to dark brown) of the solvent. The color was compared to a series of standards to provide a semi-quantitative estimate of the amount of oil on the fur. This test could be made more sensitive and quantitative by measuring the spectrophotometric absorbance of the sample at 240 nm, but this required bringing the otter to the rehabilitation center. Further research and testing are needed to verify this method of detecting oil on sea otters in the field. Animals that are unoiled should be immediately transferred to a pre-release facility or translocated outside of the oil affected area.

Acknowledgments

In addition to those previously mentioned in the text, I would like to acknowledge the many people who worked at the rehabilitation centers. Also, I gratefully acknowledge the support of Exxon Company, USA who sponsored this report and the 1989 Sea Otter Rehabilitation Program.

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Appendix 2

Remote/Mobile Triage Facilities

Transporting sea otters over long distances is stressful. For otters that have been exposed to oil, this stress can cause death or seriously complicate medical conditions. Mobile triage units would be beneficial in certain cases because they would allow staff to stabilize some animals medically before they were flown long distances to the primary rehabilitation centers. In our judgment, mortality can be reduced significantly if mobile units are employed when large numbers of otters must be captured more than 300 miles (three hour helicopter flight) from the center.

These mobile units, by necessity, should be self-contained (including electrical generators and hot water) and transportable by truck, boat, large helicopters, or fixed-wing aircraft (C-130 cargo plane); the latter may be necessary for areas inaccessible by road such as the Aleutian Islands or the North Slope of Alaska. One type of mobile facility (see illustration 2) consists of a trailer (12 ft wide and 60 ft long) that is divided into three functional sections. The largest, central section (420 ft²) is for triage and can hold up to eight otters in portable cages until they can be flown to the primary facility. Otters arriving from the capture boats are examined by a veterinarian or animal care specialist and treated for hypothermia, dehydration, malnourishment, capture stress or other medical problems. After they are medically stabilized, the otters are placed in cages and monitored. The cages are placed in a shallow, fiberglass spillway that collects waste water and drains into the sewer. A hose can be used to rinse the cages and spillway. Because heavily oiled otters have lost their ability to thermoregulate at cold temperatures, the room should be maintained at about 18° C (65° F). However, the otters should also be checked regularly to ensure that they are not overheating.

The triage area is connected by a door to one end of the trailer that provides space (180 ft²) for a veterinary clinic, communications center, and an administrative office. Blood samples from newly arrived otters are analyzed for metabolites, electrolytes and hematological variables. This information is vital for the veterinarians to diagnose and treat immediate medical problems. This area is also used

to store clinical supplies and drugs. Hot water is provided by a wall mounted, propane instantaneous water heater. The communications center consists of a VHF radio and telephone to keep in contact with the capture boats, helicopter and the primary rehabilitation facility. Administrative and animal health records are also kept in this area.

The other end of the trailer is used for sea otter food preparation (120 ft²). This kitchen is a smaller version of the one at the primary facility and consists of a stainless steel counter top for preparing the food, three sinks with fresh water for thawing frozen seafood, and two chest freezers (100 ft³ each). This is enough freezer space to store one to two weeks of food for ten adult sea otters. After the food is thawed, it is placed in plastic trays and passed through a window into the sea otter holding area. The otters are then hand fed by the husbandry staff. The trailer must be designed with external connections for water, electricity, propane, and sewage. If these amenities are not available at the site, then backup systems are required. These would consist of 250 gallon portable storage tanks for fresh water and a 5kW diesel electric generator with a 250 gallon fuel tank. The generator should be housed separately in a noise-insulated, weather-proof container. In wilderness areas, waste water from the kitchen and sea otter holding area can be drained onto the ground by running a hose several hundred feet from the trailer. Portable propane tanks can be used for the instantaneous hot water heaters and space heaters. Additional outdoor space for holding sea otters in cages, storing equipment, and for conducting other activities that require overhead shelter can be provided by portable, vinyl enclosures similar to those made by Weatherport Company (Anchorage, AK).

The staff at the mobile triage unit should include a supervisor with management and sea otter rehabilitation experience, a veterinarian, a veterinary technician for analyzing blood samples, and two animal care specialists to perform husbandry tasks including sea otter food preparation. If the mobile unit is placed in a remote area without access to hotels and restaurants, then a second trailer will be required to provide living accommodations for the staff and a kitchen for food preparation.

Appendix 3

Staff and Job Responsibilities for a Primary Rehabilitation Facility

1. Staff positions
 - a. Director
 - b. Operations Supervisor
 - (1) Husbandry Shift Coordinators (two shifts)
 - (a) Animal monitors/handlers cage cleaners
 - (b) Nursery staff
 - (c) Sea otter cleaning crews
 - (2) Animal Food Coordinator
 - (a) Kitchen staff
 - (3) Veterinary Coordinator
 - (a) Clinical veterinarians
 - (b) Veterinary pathologists
 - (c) Veterinary technicians
 - (d) Toxicologist
 - c. Logistics Supervisor
 - (1) Secretarial staff
 - (2) Personnel Housing and Meals Coordinator
 - (3) Supplies and Equipment Procurer
 - (4) Facilities Maintenance
 - (5) Security
 - (6) Transportation Coordinator
 - (a) Aircraft and ship transportation
 - (b) Ground transportation
 - (7) Communications Coordinator
 - d. Personnel Supervisor
 - (1) Accounting/payroll
 - (2) Training
 - e. Documentation Supervisor
 - (1) Archives
 - (2) Computer data entry
 - f. Public Relations Coordinator
2. Responsibilities of the Director and Staff Supervisors.
 - a. Director
 - (1) Organize and direct response operations associated with the cleaning and rehabilitation of oiled sea otters.
 - (2) Maintain contact with designated representatives of the USFWS, members of the Regional Response Team and others directly involved with the capture, cleaning and rehabilitation of oiled sea otters.
 - (3) Obtain USFWS authorization to capture and rehabilitate oiled sea otters.
 - (4) Designate and meet regularly with supervisors; establish priorities to ensure efficient and effective operations.
 - b. Operations Supervisor
 - (5) Meet with Press Relations Coordinator in order to organize press briefings and respond to press inquiries.
 - (6) Approve all requests for personnel, equipment, supplies and construction.
 - (7) Approve the discharge of personnel.
 - c. Logistics Supervisor
 - (1) Coordinate the cleaning, husbandry, food preparation and veterinary care of sea otters in the center.
 - (2) Work with the Logistics Supervisor to identify and maintain required equipment and supplies.
 - (3) Work with the Personnel Supervisor to recommend the hiring or discharge of personnel for sea otter cleaning, husbandry, food preparation and veterinary care.
 - (4) Ensure that all husbandry staff are properly trained and adequately clothed.
 - (5) Establish safety protocols to protect animal monitors and handlers from injury.
 - (6) Supervise the cleaning and care of oiled otters.
 - (7) Work with the Documentation Supervisor to ensure that proper records are maintained and that each otter is identified with a flipper tag.
 - (8) Work with the Logistics Supervisor to arrange for the purchase and delivery of seafood for the otters.
 - (9) Institute quality control procedures for the preparation and distribution of otter food to the husbandry staff.
 - (10) Coordinate with the veterinary staff to ensure proper care and treatment for otters in the center. Ensure that all otters that die in the center are necropsied by a veterinary pathologist and that tissue samples are taken for toxicological and histopathological analysis.
 - (11) Establish security procedures for personnel entering the facility. Ensure that no domestic animals enter the facility.

B. Medical diagnosis

1. Otter identification number
2. Date and time of examination
3. Overall condition and symptoms
 - a. alertness
 - b. body weight (food consumption, see below)
 - c. core body temperature
 - d. heart rate
 - e. respiratory rate (evidence of respiratory distress)
 - f. occurrence of seizures
 - g. pelt condition (includes degree of oiling)
 - h. skin disorders
 - i. appearance of teeth and gums
 - j. appearance and consistency of feces
 - k. additional symptoms and veterinary comments
 - l. comments from husbandry records
4. Blood analysis (see below)
5. Urinalysis (see below)
6. Diagnosis (veterinarian's diagnosis and recommended therapy)
7. Chemical restraint if required (type and dose)
8. Drug therapy (drug types, doses, and frequency)
9. Fluid therapy (type, quantity, and frequency)
10. Surgical intervention (full description)
11. Daily progress reports

C. Blood analysis

1. Otter identification number
2. Date and time of blood sample
3. Reason for blood sample (admission, routine, toxicology, monitoring medical treatment, etc.)
4. Laboratory performing the analysis
5. Hematology
 - a. hematocrit (%)
 - b. buffy coat
 - c. serum color (clear, hemolyzed, etc.)
 - d. erythrocyte sedimentation rate (min)
 - e. hemoglobin concentration (g/dl)
 - f. red blood cell count
 - g. mean corpuscular volume (cubic microns)
 - h. mean corpuscular hemoglobin concentration
 - i. platelets (adequate, increased, decreased, clumped)
 - j. white blood cell count
 - k. neutrophils (%)
 - l. bands (%)
 - m. lymphocytes (%)
 - n. monocytes (%)
 - o. eosinophils (%)
 - p. basophils (%)
 - q. unidentified leukocytes
 - r. Heinz bodies
 - s. other cell types and quantities
 - t. comments

6. Serology

- a. glucose (mg/dl)
- b. blood urea nitrogen (BUN, mg/dl)
- c. creatinine (mg/dl)
- d. BUN to creatinine ratio
- e. uric acid (mg/dl)
- f. cholesterol (mmol/l)
- g. triglycerides (mmol/l)
- h. alkaline phosphatase (U/l)
- i. GGTP (U/l)
- j. SGOT (U/l)
- k. SGPT (U/l)
- l. lactate dehydrogenase (U/l)
- m. total bilirubin (mg/dl)
- n. direct bilirubin (mg/dl)
- o. total protein (g/dl)
- p. albumin (g/dl)
- q. globulin (g/dl)
- r. albumin to globulin ratio
- s. iron (ug/dl)
- t. triiodothyronine (T3) uptake (%)
- u. thyroxine (ug/dl)
- v. amylase (U/l)
- w. lipase (U/l)
- x. ammonia (umol/l)
- y. comments

7. Electrolytes

- a. sodium (mEq/dl)
- b. potassium (mEq/dl)
- c. calcium (mg/dl)
- d. phosphorous (mg/dl)
- e. magnesium (mmol/dl)
- f. chloride (mg/dl)
- g. polychromasia
- h. poikilocytosis
- i. macrocytosis
- j. microcytosis
- k. nucleated RBC to WBC ratio
- l. hyperchromasia
- m. hypochromasia
- n. degree of sample hemolysis (slight, moderate, severe)
- o. comments

D. Urinalysis

- a. pH
- b. total protein
- c. glucose
- d. ketones
- e. bilirubin
- f. hemoglobin
- g. specific gravity
- h. sediment (bacteria, blood, crystals, epithelial cells, casts)



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**Results of the
Eagle Capture, Health Assessment,
and Short-term Rehabilitation Program
Following the Valdez Oil Spill**

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Presented at a special symposium

"The Effects of Oil on Wildlife"

held in conjunction with

*"The 13th Annual Conference of the
International Wildlife Rehabilitation Council"*

*Herndon, Virginia
October 17-18, 1990*

Summary

Initial concerns about the impact of the Valdez oil spill on bald eagles in Prince William Sound are being set aside, as accumulating evidence indicates the area's eagle population is generally healthy and thriving. This paper presents and discusses some of that evidence. It reviews the 1989 data collected during the Prince William Sound and Kodiak Island Eagle Capture and Short-term Rehabilitation Programs, as well as 1990 data from the U.S. Fish and Wildlife Service's (USFWS) operational field surveys.

The authors participated in an unprecedented effort to capture bald eagles and assess their health following the Valdez spill. Three teams captured 113 eagles, or about 2% of the area's estimated 5,000 eagles. Although the teams focused their efforts on capturing eagles within the most heavily oiled areas, they noted evidence of oiling on only 35% of the captured eagles.

After conducting a physical exam and rudimentary bloodwork, the teams concluded that 98 (87%) of the captured eagles met release criteria. Those birds were immediately returned to their territories. Fifteen (13%) of the captured eagles required medical treatment or cleaning, and most of these birds were transported to the International Bird Rescue Research Center (IBRRC) in Seward for short term rehabilitation. In addition, IBRRC processed 24 birds that had been delivered by the general public and, in one case, by USFWS.

The positive findings in 1989 have been corroborated by 1990 USFWS operations-related active eagle nest surveys. In May the USFWS pinpointed 1,031 active eagle nests in the general area that had been oiled in 1989. The authors' own August 1990 field observations confirmed sightings of hundreds of eaglets and recent fledglings in the previously oiled areas.



More than 5,000 bald eagles inhabit the Prince William Sound area.

Results of the Eagle Capture, Health Assessment, and
Short-term Rehabilitation Program Following the Valdez Oil Spill



Teams captured 113 bald eagles in the most heavily oiled areas during the summer of 1989 to assess their health. We released 98 of the birds immediately because they met USFWS health criteria.



Teams photographed the birds to document evidence of oiling. Records indicate that only 39 birds had even the slightest oiling. Among the oiled birds, we would typically find a portion of their tail fringe stained.

The 1989 Bald Eagle Program

Background

Shortly after midnight on March 24, 1989 the Exxon Valdez collided with Bligh Reef in Alaska's Prince William Sound, spilling nearly 11 million gallons of North Slope crude. The oil eventually fouled 10% to 15% of the area's shoreline (USFS, 1990). According to the U.S. Fish and Wildlife Service, more than 5,000 bald eagles are associated with the area's intertidal habitats (USFWS, 1989).

USFWS began to develop a program addressing concerns about the area's bald eagles shortly after the spill. Very little, if any, study had been conducted on the effects of oil exposure on bald eagles, but the raptor biologists had various concerns. There was, for example, the possibility that oil ingestion might cause harmful reactions or affect future reproduction and that external oiling would inhibit flight.

Based on such initial concerns, the USFWS developed a capture and treatment protocol for bald eagles in late May, 1989. This original protocol called for capturing and holding many of the area's bald eagles in captivity for one year. It reflected fears that all the eagles in Prince William Sound faced immediate danger, that many were heavily oiled, and that few were nesting.

USFWS directed Exxon to hire specific qualified personnel to implement the capture and long term treatment programs. As soon as weather conditions allowed capture teams to work safely in the Sound and around Kodiak in late May, two groups of three people systematically surveyed the area to identify specific eagles that might have been exposed to oil. Although the surveys focused on the heavily oiled areas, most eagles in these areas evidently were not oiled, and none appeared moderately or heavily oiled. Also, in spite of the large-scale clean-up activities, many of the birds were maintaining territorial boundaries and hunting as usual. Many pairs were even breeding, an unexpected event because of the disruptive human

activity and suspicions that food sources might have been contaminated.

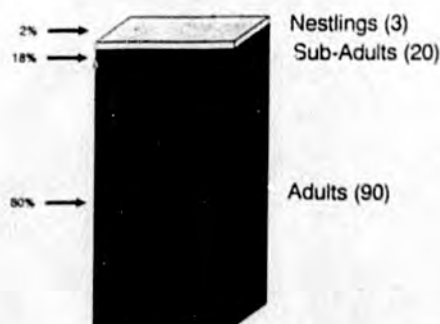
Using the information from the May 1989 surveys, the capture teams began working with USFWS to amend the initial protocol. Although most of the eagles observed during the surveys appeared to be in good health, the teams wanted to feel secure that the eagles could survive in their natural habitat. For those birds in the nesting cycle, they also wanted to be certain the adults were strong enough to feed and raise young.

The revised protocol reflected these concerns, the realities of conditions in Prince William Sound and around Kodiak, and the preference for keeping nesting pairs together in their natural habitat. The revised protocol called upon the capture teams to assess the health of as many eagles in the spill area as possible. Teams were to capture eagles, visually inspect them for signs of oil ingestion, and conduct rudimentary bloodwork. If the birds were not injured and showed no evidence of distress from oiling, teams were to release the trapped eagles as soon as possible (In practice, the entire exam required from 20 to 30 minutes). All the captured birds were to be banded with USFWS bands before release.

Capture Data

The capture teams trapped 113 eagles between June 3 and August 14, 1989. Adults represented 80% (90) of the total, with sub-adults and immatures comprising 18% (20), and nestlings, 2% (3) (figure 1.). The preponderance of adults is probably a

Figure 1
Age Distribution of Captured Eagles



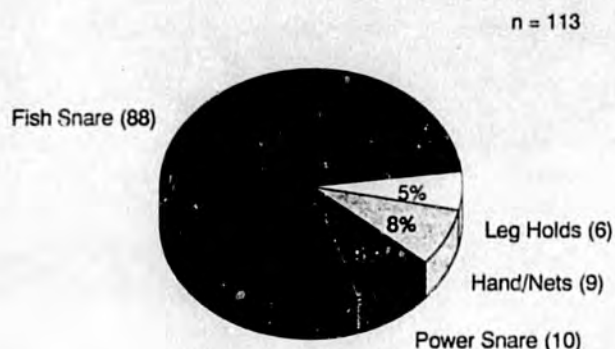
function of the season and that we targeted prime nesting locations. During the nesting season, breeding adults claim the prime areas, forcing non-breeders and younger birds to less desirable areas with more dispersed feeding sites and carrion sources (Brown, J.L., 1969).

The most successful capture technique proved to be a modified floating fish snare (see Appendix A for a description of this technique). The teams employed the floating fish technique to trap more than three-fourths (88) of the total sample. Nine eagles that had been weakened by injuries could be captured by hand or with nets. One team used power snares early in the program to trap ten birds, six of which were immature eagles. Another team used padded leg holds to successfully and safely trap four immature birds and two adults (figure 2).

Results On-Site Health Assessment

The vast majority of the captured birds met USFWS release criteria; teams immediately returned 98 (87%) of the eagles to the wild. Fourteen of the non-released eagles were transferred to IBRRC in Seward for short term rehabilitation and, in nine cases, cleaning (A fifteenth eagle from the capture teams — a severely injured eagle — was transferred

Figure 2
Capture Techniques Employed



to Anchorage, where it was later euthanized). Of the 14 birds sent to IBRRC by capture teams, 12 were returned to the wild eventually, most after about two weeks. Of the remaining eagles, one is non-releaseable, and the other which had broken its wing, is on loan from the USFWS to one of the authors for educational purposes.

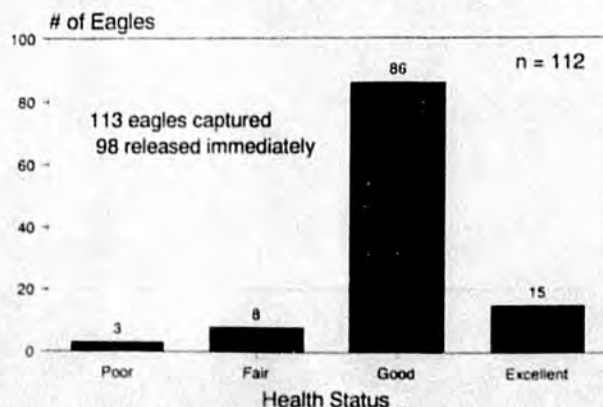
Physical Examinations

Of the 113 captured eagles, 101 (89%) were rated as being in excellent or good condition (15 and 86 eagles respectively), eight were considered in fair condition, three were in poor condition, and body condition was not recorded for one bird (figure 3). Records are incomplete for a few eagles, particularly from early in the program.

Teams marked 108 of the captured birds as alert, while three were rated as lethargic. All three of the lethargic eagles had been injured, two definitely had not been oiled, and there is no record of oiling for the third. After short term treatment by IBRRC, the three were sent to a facility in Anchorage, where they were held in captivity for one year and then released.

Physical examinations of eyes, nares, oral cavities and respiratory systems were equally positive. Except for one non-oiled bird with

Figure 3
General Health Status upon Capture



bloody nares and corneal opacities, all records noted bright eyes and clear nares. One bird's oral cavity appeared cyanotic, seven appeared pale, and 98, pink. As a result, capture teams determined that five of the birds with pale oral cavities were healthy enough for release. This determination was based on the totality of physical examination information including clinical pathology data. The average packed cell volume (PCV) of the five birds was 49%.

Capture teams also rated body condition of the eagles on a scale from one to five. A "one" would have indicated the bird was emaciated, and none of the birds received the "one" rating. A "five" indicated superior pectoral muscle development — a relatively rare condition for wild birds, particularly during breeding season (Gibson and Bloom unpublished). Only three eagles received a rating of "five." The vast majority (60) of the birds rated as a "three"; 37, as a "four"; and eight, as a "two" (figure 4).

External Oiling

The capture program documented evidence of oiling on the captured birds. Teams members took field notes and photographs for documentation (see photos attached for examples). They were particularly concerned about signs of oil around the beak, neck or vent because this would denote possible ingestion.

Records indicate that 39 eagles (35%) exhibited no evidence of oiling. In addition, degree of oiling was not specifically noted for 35 birds (31%). A blank on the form was understood to represent no oiling. Since oiling was the focus of the capture program, it is likely, but not certain, that birds without oiling notations were also non-oiled. Of the 39 eagles (35%) for which oiling was noted, one was classified as heavily oiled, three as

moderately, and 35 as lightly (i.e., spots, stains or sheens along the tail fringe or on the feet; figure 5). Most of the 39 oiled birds appeared in good condition overall. Their health ratings were as follows: five, excellent; 29, good; four, fair; and one, the heavily oiled bird, poor.

Because oiling was typically limited, often to a spot the size of a dime, capture teams would occasionally "spot clean" eagles on the capture vessel. Teams were able to wash thirty of the oiled birds and release them immediately. They forwarded the other nine birds to the IBRRC for processing and washing.

Bloodwork

Because of earlier studies of oiled seabirds, it

Figure 4
Body Condition upon Capture

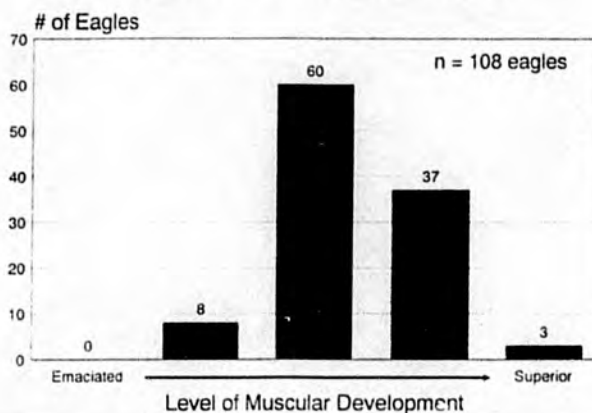
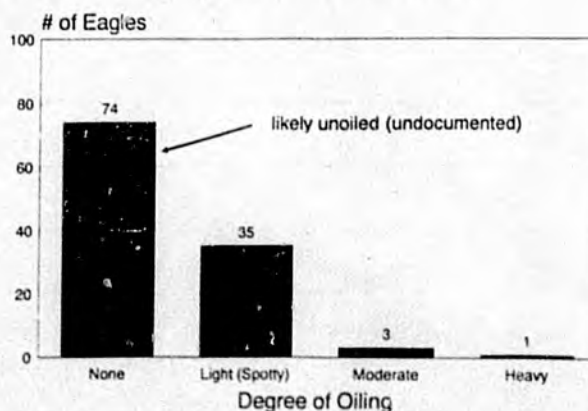


Figure 5
Oiling on Captured Eagles



was feared that eagles in the spill area might suffer from hemolytic anemia and kidney and/or liver insult (Williams, 1985; Fry, 1987). In addition, PCV is a good clinical indicator of health stamina and is an important criteria for release. To determine the PCV of the blood, each capture boat was equipped with a microhematocrit centrifuge. To obtain a sense of a bird's nutritional status, as well as get an indication of liver or kidney problems, teams measured total solids using a refractometer. Total solids are the amount of plasma substances found in healthy birds (glucose, uric acid, plasma proteins, etc). In debilitated birds, this value is often depressed.

The capture teams drew blood (approximately 10 cc's) from the brachial vein using a heparinized 20-25 gauge needle. With the same needle, the team

leader immediately made four blood smears on alcohol cleaned slides. The slides were then air dried, fixed in absolute methanol, and stored in microscope slide boxes.

In general, the results indicated that the hematopoietic (i.e., blood manufacturing) systems were in good shape. We collected 77 acceptable samples for PCV counts—10 from treated birds and 67 from immediately released birds. Among the 67 samples from immediately released birds, the minimum was 35%; the maximum, 68%; the mean, 46.6%; and the standard deviation, 5.8%. For the 10 treated birds hematocrit levels ranged from 20% to 68%, with a mean of 46.0% (standard deviation is 5.8%). Using a total of 85 samples, including 10 treated birds, total solids ranged from 2.5 g/dl to 7.3 g/dl, with a

mean of 4.1 g/dl (standard deviation is 0.7 g/dl); (figures 6 and 7). Among the 75 samples from immediately released birds, the statistical results are identical to those for the total sample of 85.

Based upon data from rehabilitated birds in captivity, the USFWS determined that rehabilitation care might be justified for birds with total solids below 4.0 g/dl or PCV below 40%. However, standards were not based on data from a wild population and were viewed as guidelines, not as firm criteria. USFWS directed capture teams to consider blood levels in the context of the birds' overall conditions. Low total solid values only compelled rehabilitation when combined with other signs of distress. With this in mind, the capture teams considered and released 17 birds with total solids below the 4.0 guideline. Release in each case was justified by the evident health of the bird.

The two on-board blood tests were micro-techniques, requiring less than 0.5 cc's of blood. The microscopic slides and the remaining blood (six to nine cc's)

Figure 6
Distribution of Hematocrit Measurements

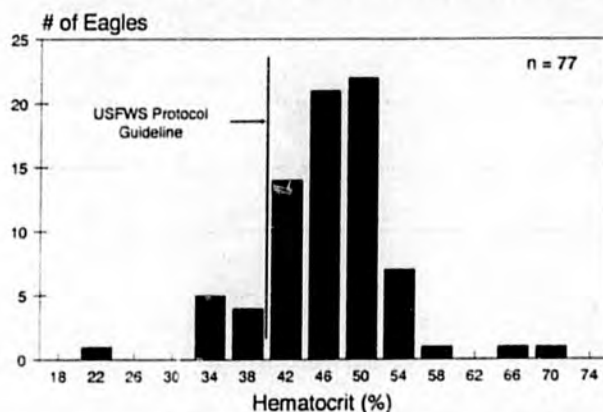
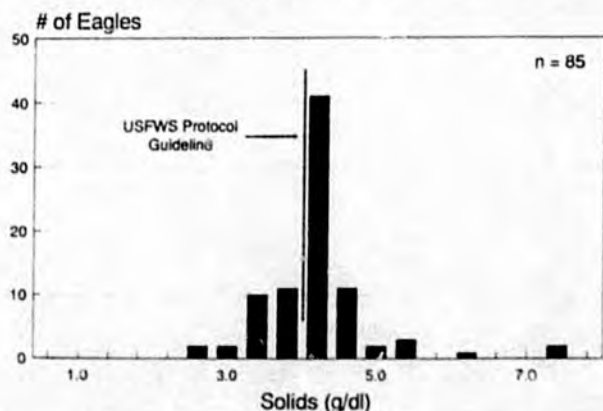
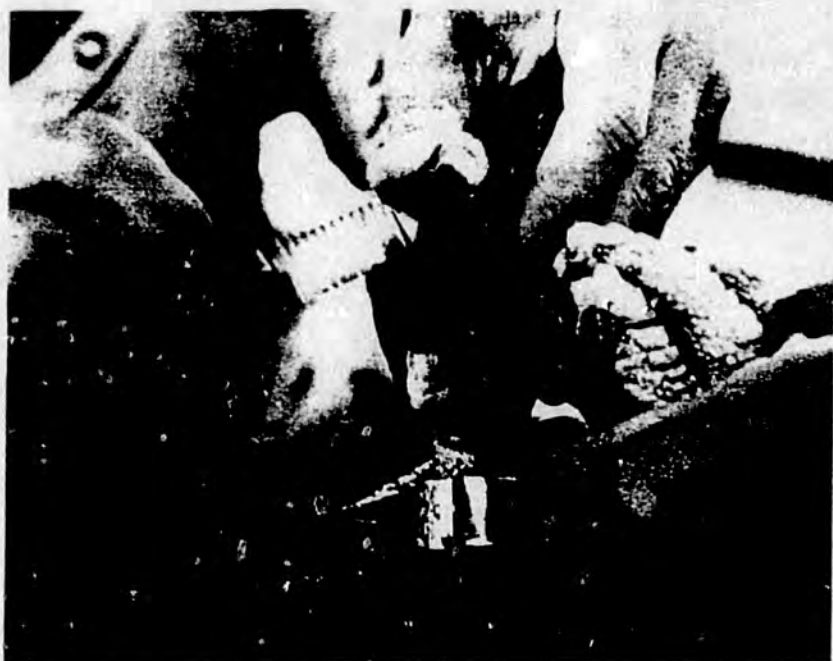


Figure 7
Distribution of Protein Measurements





In the few cases where eagles were oiled, we could usually spot clean the birds and release them immediately. Nine eagles were cleaned by the IBRRC in Seward and later released.

were put in heparinized tubes, separated, and frozen for shipment to Dr. Pat Redig at the Raptor Center of the University of Minnesota. Dr. Redig subsequently conducted comprehensive blood chemistry and hematological examinations, which have confirmed the positive findings of the field examinations (Redig, 1990).

Short-Term Rehabilitation Center

Background

The non-profit International Bird Rescue Research Center served as the short-term eagle rehabilitator following the Valdez spill. IBRRC has a long history of developing and directing rehabilitation efforts for wildlife affected by oil spills. Since 1971, IBRRC staff has consistently provided professional advice about rehabilitating oiled wildlife and, on more than 25 major spill responses, established and directed emergency oil spill rescue and rehabilitation programs.

The Alyeska Pipeline Company, which manages spill response for the Trans-Alaskan Pipeline and the Valdez area, had contracted IBRRC to serve as wildlife rehabilitators in the event an oil spill

impacted wildlife in Prince William Sound since 1979. When the Valdez accident occurred on March 24, 1989, Alyeska contacted IBRRC and requested immediate action. By early the next morning, March 25, IBRRC staff had begun to set up and operate a response.

During the next month, bird rehabilitation centers or initial care sites were instituted in Valdez, Seward, Kodiak and Homer. The IBRRC bird rescue program operated through mid-September. While the centers focused their efforts on the area's seabirds, it was also prepared to handle eagles.

In total, rehabilitation centers handled 39 eagles between April 11, 1989 and August 20, 1989. As noted above, eagle capture teams supplied 15 of those birds. Mem-

bers of the public and, in one case, USFWS personnel delivered the other 24.

Medical Evaluations and Treatments

Upon arrival at the IBRRC facility, each of the 39 eagles was given a physical examination and checked visually for oil on feathers. The veterinary staff weighed each bird and, when warranted, performed tracheal cultures to check for candidiasis and aspergillosis, common respiratory ailments. Fecal samples were examined by direct microscopy, as well as floated for parasites. We also drew blood to assess red blood cell status and to conduct serum chemistries. We used two off-site labs for bloodwork, as well as in-house lab equipped with an Abbott[™] Visions machine.

While at IBRRC facilities, eagles were monitored routinely with serial serum chemistries (approximately weekly) and hematology (PCV, total proteins, total solids, white cell counts). Beginning in mid-June, staff performed routine tracheal cultures on most of the birds. Routine parasitology proved unrewarding, but was performed on in-house birds. Eagles were photographed to document their condition while in the program.



Blood work reassured that the released eagles did not have internal problems.

Only nine of the eagles had enough oil on them to warrant cleaning (see appendix B for cleaning techniques). No parasites were found in fecal flotation or direct examinations. Staff performed tracheal cultures in-house on 14 birds for fungal/yeast growth. Only two cultures showed any growth; neither showed fungus.

On the whole, blood work performed on these birds was within normal ranges. Birds presented with old infected injuries exhibited elevated white cell counts and slightly depressed PCV, as would be expected with chronic anemia of disease. Many eagles had slightly elevated enzyme CPK, a natural occurrence given that they would have exerted significant muscle activity during trapping.

Birds from the capture teams typically had some oil to be evaluated for removal (usually spots on tail feathers) and slightly depressed total solids. After a week to ten days of rest and good food, these birds usually responded well and the total protein

levels would climb to about the 4.0 g/dl, allowing release according to the USFWS protocol.

Two of the birds from capture teams had medical problems thought to be unrelated to the oil spill. One immature bird had avian pox and was sent to the Raptor Center in Minnesota for surgical treatment of lesions. It was returned before the end of the summer and flown back into the exact territory in which it had been caught. Another was missing the tip of its wing, making it non-releasable.

In contrast, most of the birds delivered by the public had the types of serious medical injuries that are seen regularly in wildlife care centers. At least five bald eagles had fractured limbs. Various other cases included one bird that had been hit by a car, two that had lead poisoning, and others that had problems ranging from old facial wounds, leg lacerations, wing droop, swollen legs. Most of these injuries were old and were likely to be non-spill related.

The records indicate that 11 of the public-captured birds had some evidence of oiling; ten were not oiled, and there were no notations for three of the birds. Although it is not likely that many of the public-captured birds had spill-related problems, IBRRC admitted them for humanitarian reasons. Many of these birds would have died if a program to save oiled bald eagles had not been in place.

The serious medical problems of public-captured birds were reflected in hematological tests and total solid readings. The incoming PCV on this group of birds ranged from 17% to 50% with an average value of 36% — about 10 percentage points less than field captured eagles. Total solid readings ranged from 1.0 g/dl to 4.4 g/dl, with an average of 3.4 g/dl. While not dramatically depressed, this figure is significantly lower than the capture team birds.

Release Criteria

To determine whether bald eagles met release criteria, the staff conducted physical exams and pre-release blood work. Additionally, we tested eagles for flight ability in large flight aviaries or on flight lines (creance lines). We completed serum chemistries and blood counts in-house, or at Seward General Hospital. In this way, timely results could be obtained and the period of captivity could be kept as

short as possible.

Using the established protocol, IBRRC released eagles when the bird's hematocrit exceeded 40%, total solid readings exceeded 4.0 g/dl, and when relevant, medical problems had been resolved. At release, the birds were measured, weighed, and banded.

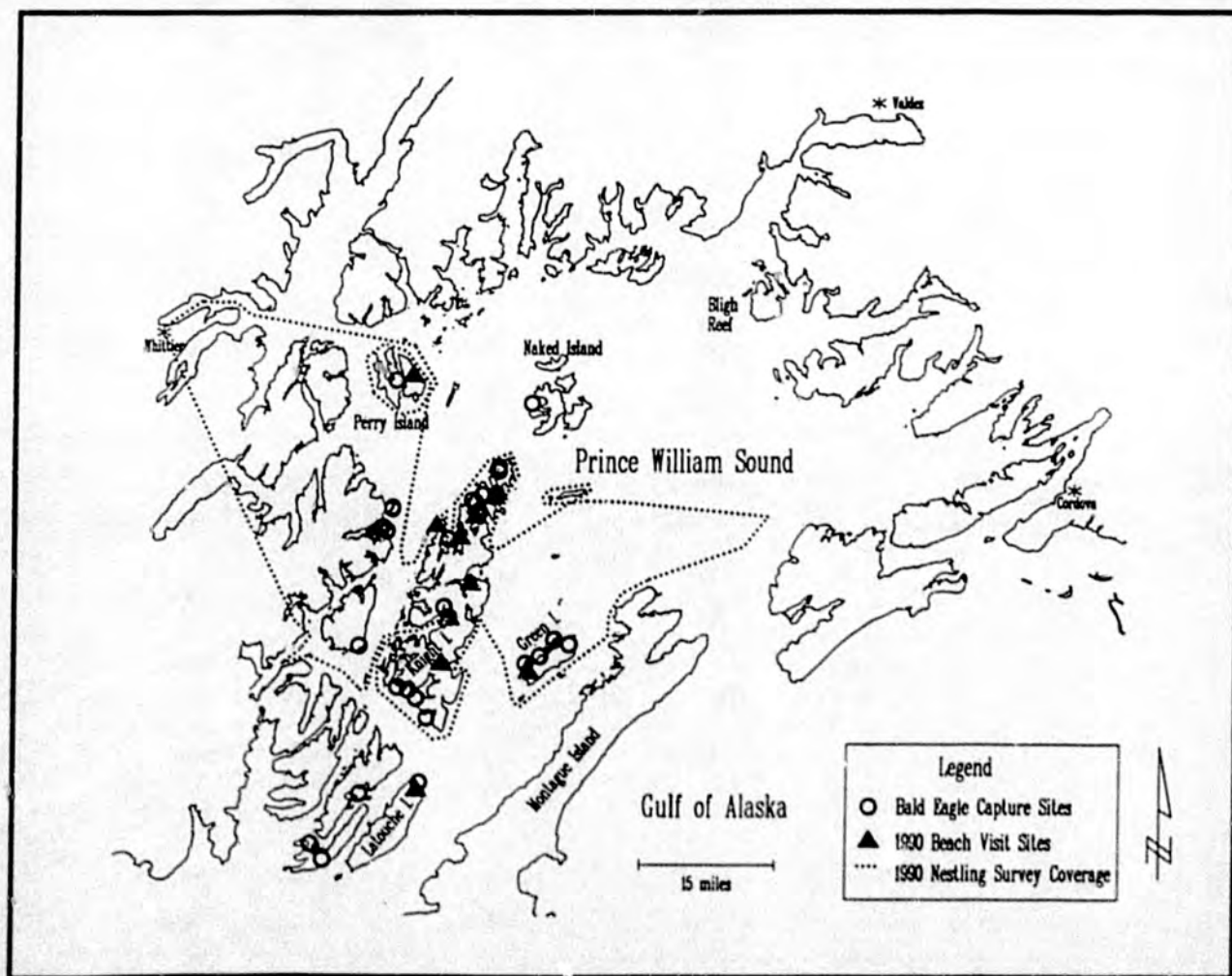
Of the 15 capture team birds, nine were released in 1989, three others were released in June 1990, one was euthanized, one is on loan from the USFWS to one of the authors for educational purposes and one is held. Of the 24 public-capture birds, eight were released in 1989 and another four were returned to the Sound in 1990. That is, 24 of the 39 birds (62%) were eventually released. Six eagles are non-releasable and remain in captivity, including four at the Bird Treatment and Learning Center in Anchorage, and one at a facility in New Mexico.

Conditions in 1990

USFWS Survey of Active Nests

In preparation for the summer 1990 Exxon beach clean-up operations, USFWS surveyed eagle nests in the oil spill area to assess whether clean-up operations might disturb nesting pairs. Their appraisals covered segments of Prince William Sound, the Kenai Peninsula, Kodiak Island, and the Alaskan Peninsula (see maps).

Wherever active nests were observed, access to the immediate area was restricted jointly by Exxon and USFWS in order to prevent the possibility of nesting loss. Initially clean-up crews and boats were prohibited from approaching closer than 1/4 mile of the nest; aircraft were not to approach closer than 1/2 mile. These restrictions were all reduced to 1/4 mile due to the program's success, and ultimately



USFWS dropped these restrictions altogether.

Geographically, the breakdown of active nests in previously oiled areas is as follows:

Region	Number of Active Nests
Prince William Sound	268
Kenai Peninsula	105
Kodiak Island	407
Alaskan Peninsula	251
TOTAL	1,031

Field Observations

The authors visited the Prince William Sound area in 1990 to gauge qualitatively the reproductive success of eagles in previously oiled areas. The trip was made in August when the nestlings were nearing fledgling age.

We observed numerous eaglets and recent

fledglings throughout the area (see photographs). In 1990, many pairs were not only occupying previously oiled territories, but they had also nested, laid eggs, incubated, and hatched chicks that had developed normally. These sightings, along with the 1,031 active nest count, are a positive contrast to 1989, when, according to USFWS, only about 200 young were produced in the Prince William Sound portion of the spill area (USFWS, 1989). If oil was still a problem, it could have most likely prevented the completion of the nesting cycle.

During our habitat observation trip, we also revisited many of the islands and bays that had been most heavily oiled in 1989. Again, the contrast between 1989 and 1990 was significant. We returned to beaches that last year had several inches of bulk oil covering everything. This year those same beaches appeared restored, not only by continuing



clean-up operations but also the natural cleansing forces of Alaska's harsh winter storms.

Our visit also coincided with the return of pink salmon to the area's spawning streams. Their presence underscored the ample food supplies available to eagles in Prince William Sound. Because these fish had been juveniles during the spill, there had been concern about the size of this year's catch. Such concern was put aside, however, as local fisherman celebrated the largest commercial catch of pink salmon in Prince William Sound ever recorded (Wall Street Journal, 1990).

Because so many birds were fledging during our visit, and because there were two chicks in many of the nests, we conclude that food sources were more than adequate. We also conclude that oil did not pose a threat to the area's bald eagles in 1990.

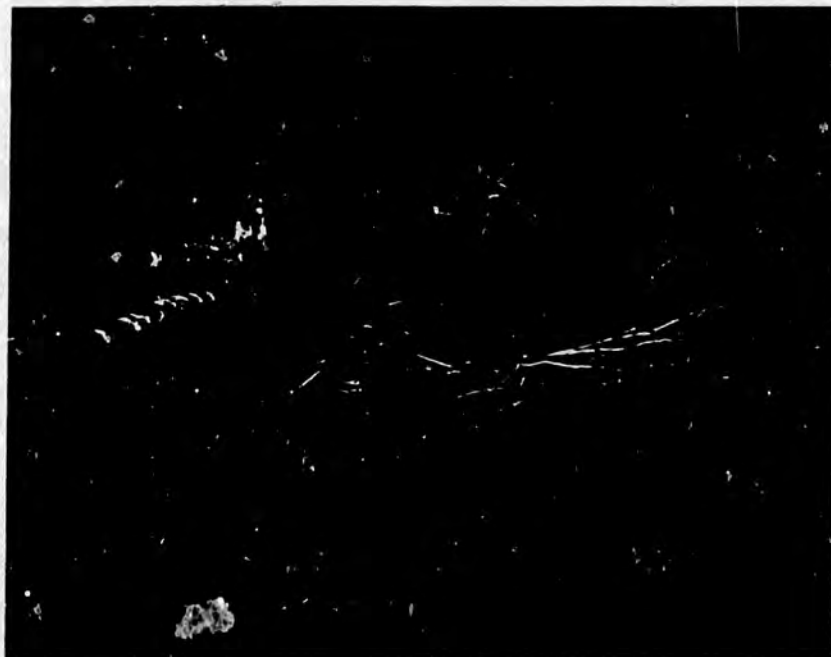
Discussion and Conclusion

The evidence from the 1989 Eagle Capture and Assessment Program, as well as the qualitative observations in 1990, indicate that the Valdez oil spill was not the catastrophe for bald eagles that we had originally feared. There was indeed eagle mortality in 1989. USFWS recovered 153 carcasses during the summer of 1989, and many of those were likely victims of the oil spill. But preliminary fears that most of the area's estimated 5,000 eagles would die have not been supported by the facts. A year after the spill, the bald eagle population in the area seems healthy.

Most theories about why the eagles tolerated the oil spill so well are related to the bird's physiology (Duke, 1986). Like other birds of prey, bald eagles have the ability to collect in their crop undigestible products such as the large bones, fur, and feathers of their prey. The eagle egests this material daily. It may be that the eagles can egest tar balls in this manner without an effect to the bird (Duke, pers. comm.).

There is, of course, significant doubt about whether most eagles even ingested oil. It seems that eagles could have easily found non-oiled areas in which to hunt and eat. First, large portions of Prince William Sound and the Gulf of Alaska were never oiled in 1989. The tanker spill impacted only about 10% to 15% of the area's linear shoreline. Second, because the pattern of oil dispersal was dictated by the ocean currents, the oil was not evenly distributed in 1989. Where one beach might be loaded with crude, another only a mile away might be totally clean. Finally, within a couple of months, there was little oil left on the waters in Prince William Sound (Neff, 1990). This is important because the primary prey for eagles in the area is fish.

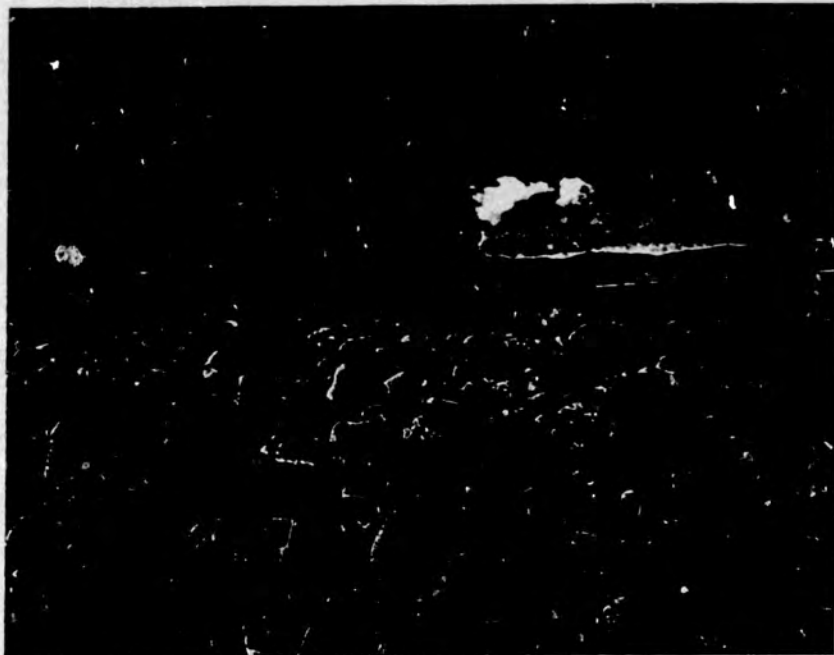
While initially there were reports that the eagles were attracted to oiled carrion, the capture teams did not notice the bald eagles hunting in oiled areas. We trapped eagles in some very heavily oiled areas in 1989, but the captured birds were usually not only healthy but also clean (see attached photos). We also found that eagles would ignore our floating fish snares if they were set near an oiled shoreline (within 30 meters) or other contaminated areas. Only after teams reset in a clean area within the same territory would a bird respond.



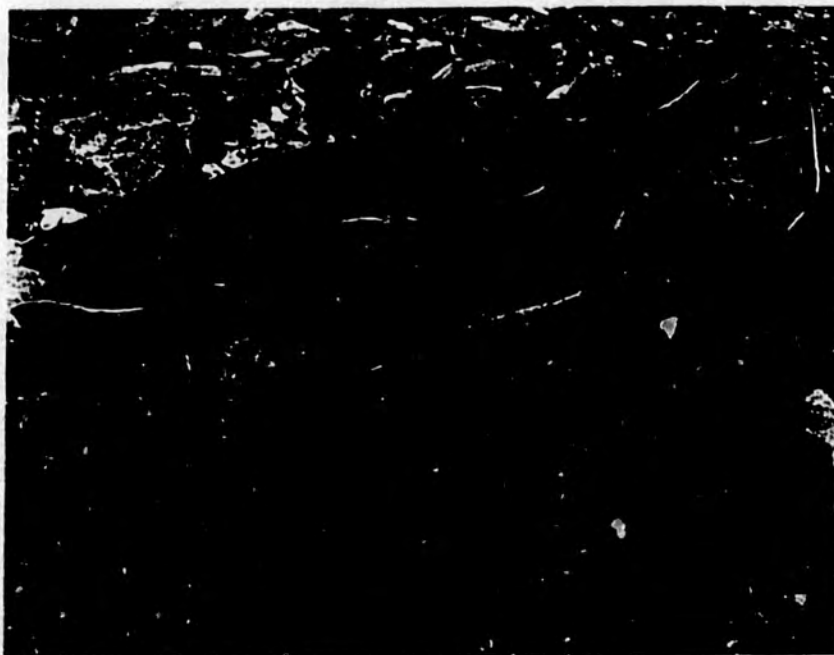
USFWS pinpointed more than 1,000 active eagle nests in 1990. Many held more than one chick.

The nature of crude oil also might have mitigated the impact of the oil spill. Within a few days after the spill, most of the volatile components of crude had already evaporated (Neff, 1990). Within a few weeks, the crude had altered chemically enough that it posed a reduced threat to wildlife. By the time it reached Kodiak Island, the oil had formed into a biologically inert oil-water emulsion commonly called mousse. Therefore, few birds were oiled.

Whatever the reason, the bald eagle population in Prince William Sound is evidently thriving. In spite of the Valdez oil spill, we can be generally optimistic about the future of the Prince William Sound bald eagles.



The Prince William Sound eagle habitat has essentially been cleansed of oil, thanks to natural processes and clean-up efforts. What little oil remains has weathered to the point that it would not present a problem for eagles.



Salmon returned to Prince William Sound in record numbers this year. These ample fish stocks are good news for eagles, who prey primarily on fish for food.



Acknowledgements

A paper of this nature would not have been possible without the commitment and efforts of many.

We express special appreciation to Valdez team members Teryl Grubb and Glenn Stewart and Kodiak I team members Dick Anderson, Linda Spiegel and Robert Haussler, to Harry Dodge, who served as bear guide for both Kodiak teams. A special note of thanks to the crews of the Myra Jean and the Maricor, as well as many fine pilots, with whom we weathered many storms. Also thanks to Greta Angason of IBRRC for developing the database that made much of this paper possible.

We specifically thank Phil Schempf of USFWS for introducing us to the "Robards" trapping technique, and to Dave Harlow and staff at the Anchorage USFWS for working with us to develop protocols under crisis conditions. Thanks to Ed Henckel, Judy Henckel and Peter Harrity of the Kodiak II capture team, who helped refine the capture techniques and gave helpful advice on this paper.

We are grateful as well for the advice and encouragement given by Pat Redig and Peter Bloom. Also to Pat Redig's staff (Jean Dunnette, Paula Lind, and Barbra Talbut) at the University of Minnesota Raptor Center for their roles in the medical assessment.

In addition, we thank Exxon for supporting the 1989 Eagle Capture, Assessment and Short-term Rehabilitation Program, as well as for their review of this paper.

Finally, we want to underscore our appreciation of families, friends and colleagues who understand our extended absences from home and offer unflagging moral support.

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Appendix A

Eagle Capture Techniques

While capturing bald eagles is always a challenge, conditions in Prince William Sound and Kodiak Island made trapping even more difficult than usual. Such conditions inspired the capture teams to refine trapping techniques. This appendix describes the development of the technique that proved superior.

The teams considered four general capture techniques: 1) net gun; 2) power snares; 3) padded leg-holds; and 4) floating fish snares. Because of the Sound's harsh weather, occasionally violent seas, and near freezing water temperatures, the net gun techniques were considered too dangerous to employ. The risk of injuries or fatalities for the birds and the capture teams was simply too great.

Land sets were used on a limited basis with some success. In June, the first team based in Kodiak employed power snares to capture eight birds, six of which were immature eagles (immature birds appeared to be more susceptible to carrion-baited traps). The Valdez team caught six eagles, including two adults, using leg holds. Trap safety did not present any problems with either technique, but conditions such as the following did preclude more extensive use:

- Tide shifts of 20 feet and more prevented teams from using shoreline sets for extended periods.
- Extended daylight made unobserved placement difficult.
- Other native wildlife, most notably bears, would often abscond with the bait.
- Because all animal carcasses in the spill area were picked up for necropsy studies, bait for the traps could not be found in the area easily (The most successful bait came from a single seal carcass, which was hauled around for several weeks).
- Purchasing fish stocks from local fishing villages also proved futile. The local bear population would often devour the cache before it could be used.

The capture method of choice became the floating fish snare. Used historically by the USFWS in the area with great success, the general technique is based on the "Robards method" (unpublished citing and Cain and Hodges, 1989 *Journal of Raptor Research*). We refined the technique to meet the peculiar conditions of Prince William Sound, as well as seasonal conditions and feeding habits.

The floating fish snare is an eagle-triggered multi-noose system. For bait, we preferred either trout or black cod ranging from 20 cm to 30 cm in length. Eagles seemed disinterested in herring, perhaps because the oily sheen it creates either seemed distasteful or because the sheen made the snare more visible. An attempt was also made to bait with seal blubber, but it was so soft that nooses would slip from it.

To enable floatation, two methods were used. If the fish had been gutted, we sewed a styrofoam plug into the abdominal cavity

with cotton thread. If not, we carved a styrofoam plug for each fish and inserted it behind the gill. A single, high density styrofoam plug is recommended. If the eagle escaped with and ate the styrofoam, it would be best able to cast the single piece.

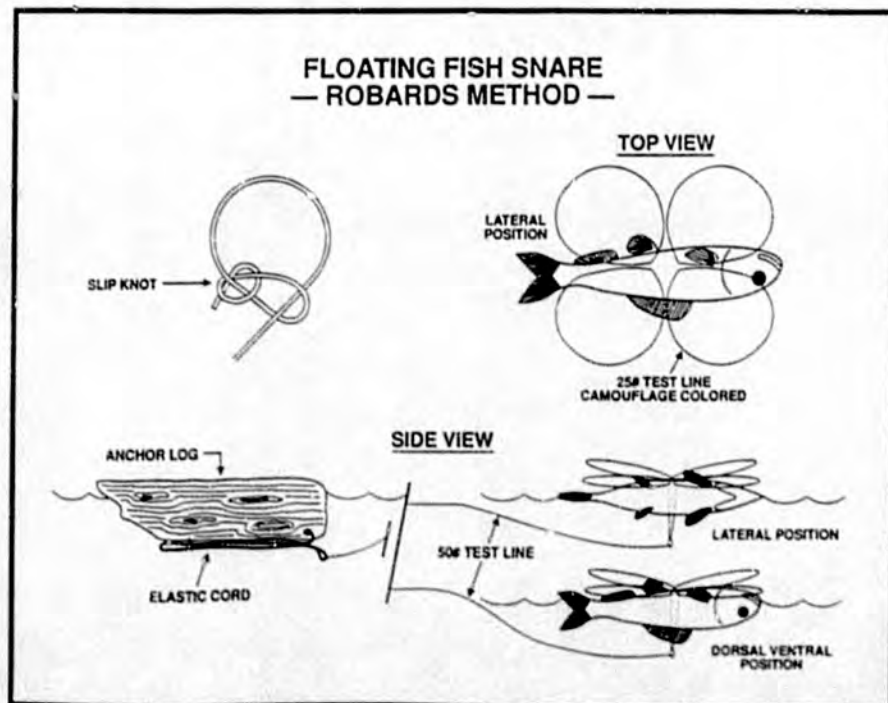
We configured a clover-leaf shaped noose (see illustration) using 25 pound test clear monofilament line. Four 18 inch segments were tied into four slip-knot nooses, each about four inches in diameter. A hole was punched through the dorsal, the styrofoam plug (if necessary) and the ventral at the center of the fish. We tied the four nooses to a separate 25 pound monofilament line that ran through the fish and connected to a bungie cord, which was in turn attached to a log. The nooses protruded from the dorsal side of the fish, clustered above the fish and stood clearly out of the water (The bait floats ventral-side up). Knots were tied at the ventral and dorsal openings to provide stability to the snare. If the punch holes were so large as to inhibit stability, they were reduced in size with a few stitches of cotton thread. A second variation of the floating fish mounted the nooses on the fish's lateral side with all other specifications remaining the same as the dorsal ventral version.

The size and shape of the anchor log was crucial to capture success. If the log offered too much resistance, the eagle would drop the bait before the noose tightened firmly. We found a cylindrical log approximately two feet in length and four inches in diameter was ideal.

Before setting the trap, an eagle was located on a hunting perch overlooking the water. A team using a skiff would place the fish in direct view of the eagle. The distance between the snare and the eagle was usually between 100 and 200 meters, depending upon tide and wave activity. The skiff moved away from the snare but kept both the bird and the trap constantly in sight. The skiff had to be prepared to seize the eagle within 45 to 60 seconds of ensnarement.

Once caught in the noose, the eagle would lift the fish and the anchor log from the water with little difficulty. However, the pendulum motion of the log would inhibit the bird's flight, and the weight would bring the eagle quickly and gently to the water's surface. The team on the skiff motored into place to seize the eagle, restrain its wings, and place a hood. The bird was transported immediately to the main vessel for processing.

As improvements were made in snare setting techniques, the capture success rate rose. Teams initially used 50 pound monofilament line for the noose configuration, a large block-shaped log as the anchor, and water surface noose placement. Capture success improved about 75% when teams began employing the more difficult to see 25 pound monofilament, the less resistant log, and the above water noose placement.



Appendix B

Short-term Rehabilitation Techniques

Nine of the bald eagles delivered to IBRRC during the Valdez oil spill required cleaning. As far as we know, our care and treatment of these birds comprise the wildlife rehabilitation community's entire experience with oiled bald eagles.

Cleaning and rehabilitation methods for bald eagles are similar to those used for other oiled birds, but there are important differences. Eagle feathers, for example, absorb rather than repel water. In addition, eagles are capable of inflicting serious injury to unwary staff.

Because cleaning can be stressful, we stabilized all eagles for at least 24 hours before initiating treatment. Un-hooded eagles were housed in individual wooden mews (8' x 8' x 6' H) with netted tops covered with sheets. Natural perching was provided.

Before cleaning, staff placed hoods on the eagles to block visual stimuli and to calm the birds. Three or more people held the eagle as washing proceeded. We wrapped the talons in sturdy tape, and one person was responsible for holding the head at all times.

We used a solution of fresh water and 1% Dawn dishsoap for cleaning. A large circular metal bucket (about 30 gallons) served as the cleaning tub. Depending on degree of oiling, cleaning required from 30 to 60 minutes. Rinsing, which took place in the same stalls as were used for seabirds, required about an hour.

Because eagle feathers had become saturated with water during cleaning and rinsing, staff returned the birds to the wooden mews for drying. Pet dryers were placed in windows and heated the mews to 95 degrees F. The birds would perch until completely dry, usually about six hours.

One of the cleaned birds had broken its wing, and it was transferred to Anchorage. Staff placed the other eight birds in one of two outdoor flight pens (32' L x 24' W x 16' H) until they could be released. We also equipped these pens with natural perches.



The Abundant Bald Eagles of Prince William Sound, Alaska



Alaska's Prince William Sound encompasses what may be the world's largest concentration of bald eagles. Experts like Miguel Colón have been studying the area's eagles since the World War II occupation there. In March 1980, the results offer good news.

February 1991

More Than 5,000 Eagles and Eaglets

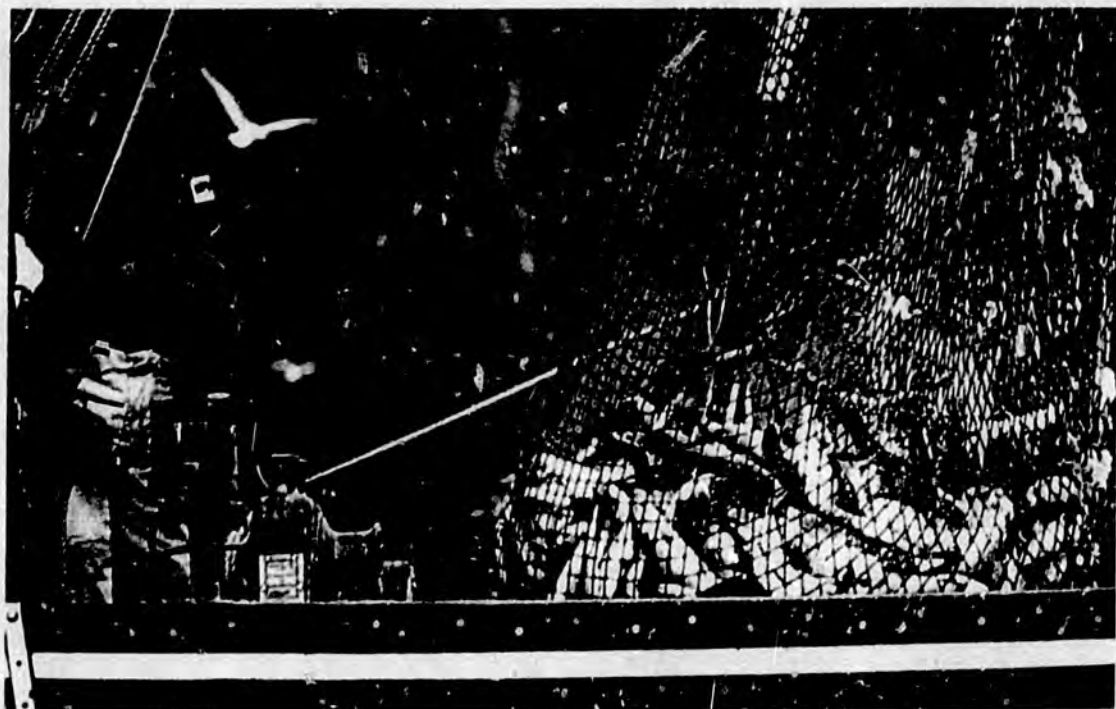
Prince William Sound is a near perfect habitat for the bald eagle. Thanks to ample food sources and shoreline forests for perching and nesting, more than 5,000 bald eagles make the area their home.

Biologists believe the population is a "saturated" one. That is, the environment could not support a larger stable eagle population.

In 1990, the U.S. Fish & Wildlife Service pinpointed more than 1,000 active eagle nests in the area.



More than 1,000 active eagle nests were pinpointed in the area during 1990 by the U.S. Fish & Wildlife Service.



Eagles and humans alike feasted on the 1990 record-breaking pink salmon catch.

1990's Record Fish Harvests

Many of Prince William Sound's eagle nests support more than one chick. That is unusual, since eagles in

most places find it too difficult to secure enough food for more than one youngster.

But food is not a problem in Prince William Sound. The eagles can rely on the area's renowned fish stocks for prey.

1990's record-breaking commercial salmon and herring harvests reflect the abundance of fish stocks in the area.



Less than 20% of the Prince William Sound area coastline was oiled in 1989. Today, the shorelines are essentially clean.

Clean, Nearly Recovered Habitat

Following harsh winter storms and two summers of clean-up operations, Prince William Sound is essentially cleansed of oil from the Valdez spill. By the end of 1989, there were no oil slicks on the water's surface and the small amount of oil that remained had "weathered" (i.e., changed chemical composition) and presented no threat to eagles.

Immediately after the accident, eagles were able to find non-oiled areas in which to hunt fish. The tanker spill impacted less than 20% of the area's shoreline. Also, because the pattern of oil dispersal was dictated by the ocean currents, the oil was not evenly distributed in 1989. Where one beach might have been covered with crude, an adjacent beach might have been totally clean.

Healthy, Thriving Eagle Population

Immediately after the 1989 oil spill, many people feared the worst and worried whether eagles would be able to recover from the spill. Now, nearly two years after the spill, the evidence shows that eagles and eaglets are thriving in the area.

The Valdez spill was an unfortunate accident and everything reasonable should be done to prevent another spill. Nature's restorative powers should not be taken for granted.

Yet, now that the evidence shows that the eagles are doing well, we can be grateful for nature's resilience.

Now that the evidence shows that eagles are doing well, we can be grateful for nature's resilience.



Marge Gibson has focused her life on caring for birds of prey through research, education and rehabilitation. In 1989, she led a team of eagle experts who captured Prince William Sound bald eagles to evaluate their health following the Valdez oil spill.

If you are interested in more details about the Prince William Sound bald eagles, please write to: Exxon Company, U.S.A., Eagles, P.O. Box 2180, Houston, Texas, 77252-2180 for a technical report entitled "Results of the Eagle Capture, Health Assessment and Short-term Rehabilitation Program Following the Valdez Oil Spill" by Marge Gibson and Jan White, D.V.M.



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**Evaluating the Long Term Effects
of Crude Oil Exposure in Sea Otters:
Laboratory and Field Observations**

Terrie M. Williams, Ph.D.
International Wildlife Research
Kailua, Hawaii 96734

Presented at a special symposium

"The Effects of Oil on Wildlife"

held in conjunction with

*"The 13th Annual Conference of the
International Wildlife Rehabilitation Council"*

*Herndon, Virginia
October 17-18, 1990*

Summary

Sea otters continue to inhabit the area that was impacted by the March 1989 Valdez oil spill. Their presence raises questions about the long term effects of the spill and the ability of the habitat to support sea otters.

To examine the long term effects of exposure to petroleum hydrocarbons on sea otters, we monitored the general health, fur condition, blood parameters, and behavior of twelve sea otters placed in captivity following the Valdez oil spill. We compared the behavior and coat conditions of these captive otters to wild otters residing in previously oiled areas of Prince William Sound and the Kenai Peninsula, Alaska. In addition, we evaluated the current suitability of the area's habitat for sea otters.

Major findings of the study are:

1. The current prognosis for captive otters that survived the initial effects of hydrocarbon exposure is good.

2. Petroleum hydrocarbon levels in the blood of captive otters returned to background levels within twelve months of the spill.

3. Clinical evaluations indicate that captive otters gradually recovered from poor thermoregulatory control, respiratory distress, and anemia which were associated with short term exposure to crude oil.

4. Eighteen months after the Valdez spill, crude oil was found only on isolated sections of shoreline. In addition, the oil had weathered so that it presented little if any threat to sea otters.

5. Several hundred sea otters were observed eating, grooming, and resting in previously oiled areas of Prince William Sound and the Kenai Peninsula.

6. Captive and wild otters were reproductively active. One captive female, which had been moderately oiled, gave birth to a pup within one year of the spill. Many females with pups were observed in previously oiled areas of Prince William Sound.



Sea otters continue to inhabit the area of the 1989 oil spill.

Introduction

Previous studies have demonstrated the vulnerability of sea otters (*Enhydra lutris*) to the detrimental effects of crude oil (Costa and Kooyman, 1982; Davis et al., 1988). Sea otters face two types of problems from exposure to crude oil. While external contamination of the fur results in decreased insulation (Williams et al., 1988) and potentially lethal hypothermia, internal exposure to petroleum hydrocarbons contributes to another set of health problems. We diagnosed pulmonary emphysema, anemia, and hypoglycemia (low blood sugar) in otters contaminated during the Valdez spill. The incidence and severity of such problems correlated with the date of exposure, and hence, with the extent of oil weathering.

From the perspective of the otters' health problems, the Valdez spill can be divided into two distinct periods. During the initial phase, lasting



Many females with pups were observed in the previously oiled areas.

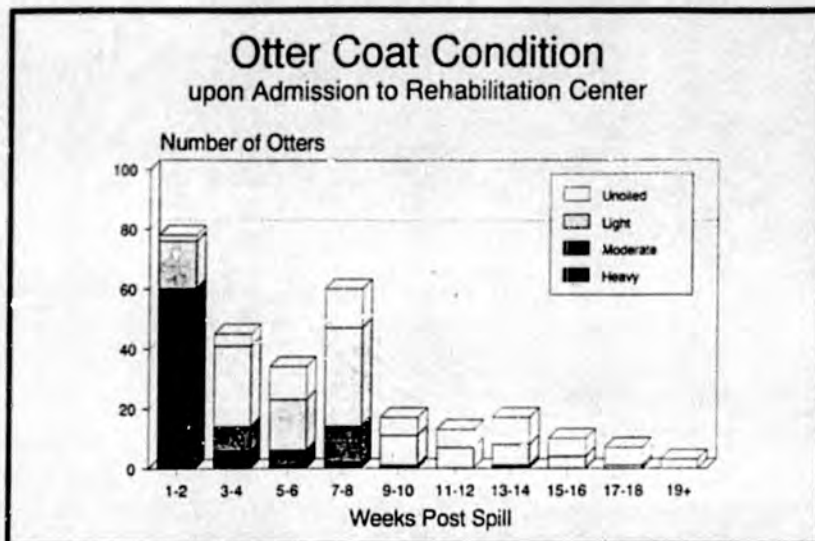


Figure 1. Degree of oiling on the coats of sea otters on admission to the rehabilitation centers. Note the rapid decline in the number of heavily and moderately oiled otters 3 weeks after the spill.

three weeks, contaminated otters showed the greatest degree of oiling (figure 1), encountered oil containing the most harmful crude oil components, and had the highest incidence of severe health problems. Although the rehabilitation program lasted several months, 54% of the deaths in the centers occurred during this initial three week period. During the second phase, 70% of the otters captured within the spill area were lightly oiled or uniled. These animals were probably exposed to fewer harmful components, had comparatively fewer health problems and, hence, greater survivorship (Williams et al., 1990).

Primary concerns for otters that survived the initial phase of the spill included: 1) long term effects due to oiling; and 2) continued contamination from residual oil in the habitat or in food items. To examine the former, we monitored the health of eight adult sea otters (seven females, one male) and four otter pups (three females, one male) for twelve months after the spill. For each



Nearly 18 months after the spill, oil was limited to isolated sections of beach. In most areas the oil had weathered so that it presented little threat to the otters.

animal, we determined: 1) general health; 2) body weight; 3) coat condition; 4) blood chemistry and hematology; and 5) reproductive status.

All of the adults in this study were captured during the initial phase of the spill and were severely impacted by the oil. Unlike the 197 adult otters that had been released back into the wild after rehabilitation, these eight adults were judged unsuitable for release and were therefore transferred to seaquariums for long term care. The pups used in this study were admitted to the centers during the latter phase of the spill (table 1).

We determined the likelihood of continued oil contamination in wild otters by assessing habitat conditions in previously oiled areas of Alaska. Major goals were to evaluate the condition of beaches and coastal waters in terms of the potential impact on sea otters, and to observe the general behavior of sea otters in previously oiled areas. These August 1990 field studies were qualitative observations; we do not consider them comprehensive. However, when compared to observations made in 1989, these studies provide a framework for evaluating general changes in the sea otters' habitat.

Status of Captive Otters

The condition of captive otters is summarized in Table 1. Several factors were assessed including coat condition, health status, body weight, blood parameters, and reproductive status.

Coat Condition

A water repellent coat is essential for thermoregulation in sea otters. Therefore, it was important to thoroughly clean fur that had been contaminated with oil. The amount of oil on the fur (i.e., the degree of oiling) varied among the otters brought to the rehabilitation centers (figure 1). Rankings ranged from heavily oiled to unoiled, and reflected the percentage of surface area covered and

the level of saturation to the skin (Williams et al. 1990). Five of the eight adult otters used in the study arrived at the rehabilitation center moderately or heavily oiled; the two other adults were lightly oiled.

All of these animals were cleaned successfully using methods outlined in Williams et al., 1988 and Davis et al., 1988. Because of the loss of natural oils from the washed fur (Davis et al., 1988), a seven to ten day delay in the recovery of water repellency is normal. Grooming activity by otters facilitates restoration of the oils and the original condition of the fur. Until then, areas of the pelt will saturate when the otter enters the water.

In the rehabilitation centers the pelt restoration process was complicated in clinically ill sea otters. These animals were often lethargic, did not groom, and therefore had consistently poor coats. Following several weeks in the rehabilitation centers, the animals began grooming and coat condition gradually returned to normal. By August 1989, coats of the adult otters had fully regained water repellency and remain in good condition.

The fur of sea otter pups also requires constant care to remain in good condition. In the wild, this

activity is provided by the mother; in the rehabilitation center members of the husbandry staff groomed the pups. In contrast to the adult otters, the sea otter pups were captured 5-10 weeks after the oil spill and arrived unoiled at the center. Although washing was not necessary, towel drying and daily combing were required to remove mats from the pups' hair. After two months in captivity the pups were able to groom themselves, no longer requiring human assistance. The fur of the pups has remained in good condition since December 1989.

Health Status

During the initial phase of the spill, sea otters showed a wide range of health problems (i.e., gastrointestinal dysfunction, respiratory distress, poor thermoregulatory control, anemia, and fluctuations in blood cell counts). Some of these conditions, particularly gastrointestinal problems and stress, may have been complicated by captivity. In addition, oiled sea otters often demonstrated chronic bloody nasal discharge, lethargy, diarrhea, and poor motor coordination in the water (Wilson *et al.*, 1990). Subcutaneous emphysema was documented in three study animals that were heavily oiled and captured during the initial phase of the spill (table 1). Body temperature was variable in these animals and ranged from 95°F to 102°F during the first few days in the rehabilitation centers (Body temperatures of healthy otters range from approximately 99°F to 100°F; Costa and Kooyman, 1982).

The general health of the captive adult otters improved after cleaning. Thermoregulatory problems were quickly corrected as water repellency of the coat was regained. Recovery from the initial health problems occurred within 3-4 months of exposure to the oil. Gastrointestinal problems were often corrected after two weeks, but the anemia persisted for over 45 days (see below). Corneal damage in one otter and minor locomotor problems in two

other animals persist, but these conditions do not appear to impair their general health. Treatments (i.e., antibiotic therapy) were unnecessary after September 1989. The appetite and activity level of the captive otters remain high, and indicate a general recovery from the initial effects of oil contamination. Currently, the health status of captive otters is good.

Unlike the adults, the sea otter pups did not appear oiled when captured. Often the pups were found abandoned in the wild or were separated from female otters that were unable to care for them. Despite the absence of surface oiling, general health of the pups on arrival at the rehabilitation centers was varied. For example, body temperatures were highly labile, three of the pups were underweight and anemic, and diarrhea was common until the diet was adjusted.

Raising sea otter pups in captivity is difficult because of their nutritional and thermoregulatory demands. Yet, the appetites of the otter pups indicated that the animals quickly acclimated to the seaquariums. The health of the pups has been good to excellent from October 1989 to present. One exception is a male pup (SW106) which has experienced several health problems (hypoglycemia, ane-



Sea otter fur usually returned to normal within a couple of weeks after cleaning. The lighter brown areas indicate water repellency.



Good appetites and increased body weights indicated that the otters were in good health.

mia, acute nephritis, and a moderate nonspecific infection). This animal showed a gradual improvement during November and December 1989, but it remains in guarded condition. Reasons for his persistent problems include oil related and non-oil related factors (i.e. an individual response to captivity or susceptibility to disease, exposure to petroleum hydrocarbons before or after birth). Because of the absence of surface oiling, it is unlikely that external contamination was a significant factor.

Body Weight

The resting metabolic rate of sea otters is almost 2.5 times higher than other similarly sized mammals (Costa and Kooyman, 1982), and results in a voracious appetite. Inadequate food intake or poor nutrition will accelerate weight loss in these animals. Because lethargy and anorexia were common problems in oiled otters, many of the animals were underweight during the first weeks in the rehabilitation centers. As the otters' health improved, their appetites returned and body weights quickly

increased. From March 1989 to January 1990, the body weight of non-pregnant adults increased an average of $12.3 (\pm 2.3 \text{ lb.})$ (figure 2). Similarly, all of the pups gained weight, with a mean increase of $22.6 (\pm 3.0 \text{ lb.})$ during the first nine months in captivity.

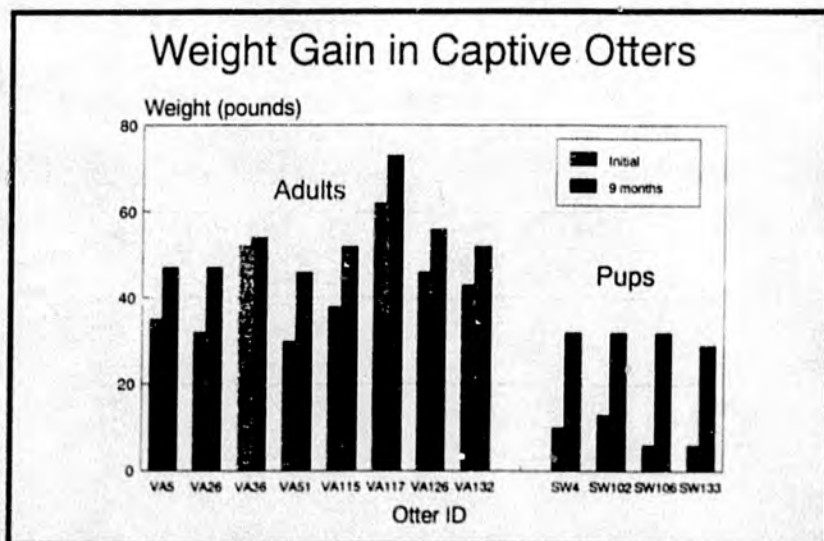


Figure 2. Changes in body weight of adult sea otters and sea otter pups on arrival at the rehabilitation centers and after nine months in captivity.

Blood Parameters

Blood panels were generated throughout the rehabilitation process and provided a good indication of the health status of the otters. When the oiled animals arrived at the rehabilitation centers, hypoglycemia and anemia were commonly diagnosed (Wilson *et al.*, 1990). White blood cell counts were quite variable in many of the otters (table 1). Much of this variability was attributed to the presence of infection or possible immuno-suppression.

Recovery from many of these conditions occurred within four months of captivity. White blood cell counts, creatinine levels, and enzyme levels (SGOT, SGPT, and CPK) returned to normal in all of the study animals except for two adults and one pup. Periodic elevations in white blood cell counts and enzymes (CPK, LDH, and to a lesser degree SGOT) continued to occur in the two adults. The male pup shows consistently abnormal blood variables (elevated WBC and LDH, anemia) that are attributed to infection.

Anemia persisted for approximately eight weeks in 11 of the sea otters (figure 3). Hematocrit of these animals was less than 40.0% during the first two months after the spill. This increased to 47.4% during the third month and was within the normal range for captive otters (50.0 - 62.0%; T.D. Williams, per. comm.) after four months. The hematocrit of the otters has remained normal since that time.

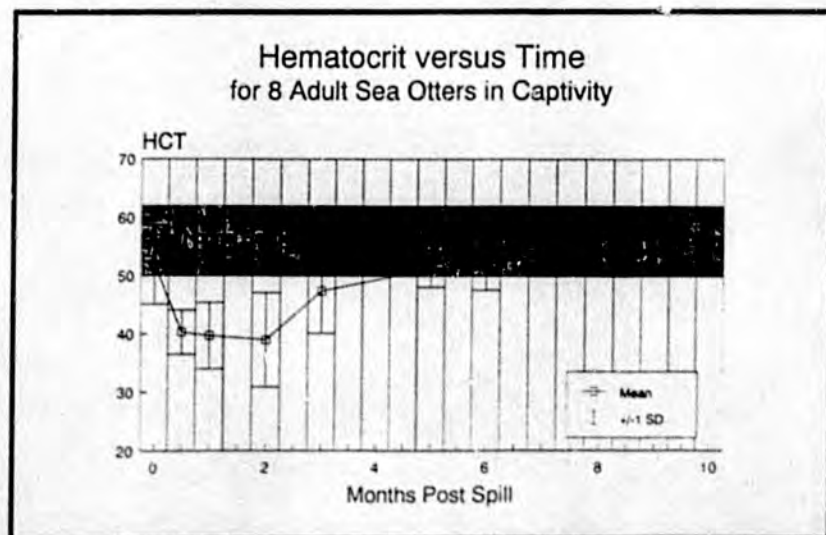


Figure 3. Hematocrit of adult sea otters in relation to time post spill. Mean values $\pm$ 1SD are indicated.

In addition to the routine analyses, we determined total paraffinic hydrocarbon (TPH) levels in the blood samples. TPH in blood provides an indication of systemic exposure to oil and can be useful in predicting survival (Williams, in prep.). We found that the concentration of TPH ranged from 19 ppm to 800 ppm in sea otters admitted to the rehabilitation centers (Williams *et al.*, 1990). Levels above 80 - 120 ppm were associated with mortality. In comparison, total paraffinic hydrocarbon concentration was insignificant in captive sea otters examined twelve months after exposure to crude oil (table 1). Such levels are well below the lethal threshold range determined for otters.

Reproductive Status

Mating among rehabilitated otters was often observed when male and female adult otters were housed together. The male in this study, VA117, became active in August 1989 after introduction into the female pool. He recently sired a healthy pup (see below). The females varied in responsiveness to VA117; although two animals were reproductively active in August 1989, the remaining females did not appear active for three to four months after that date. Currently, all of the captive adult otters are demonstrating reproductive behaviors.

In the wild, female sea otters are capable of producing a pup annually. However, age of the female, health, previous pregnancy among other factors will affect the reproductive interval (Rotterman and Simon-Jackson, 1988). The average time between copulation and birth ranges from 6-7 months for wild otters to 7-8 months for captive animals. Two of the four reproductively active females showed evidence of pregnancy during the study period. Serum progesterone for one animal sharply increased to approximately 6500 pg/ml in August 1989, and indicated possible pregnancy. However, serum levels gradually decreased over the following two months with no ensuing gain in weight. Another female, VA126, had

serum progesterone levels of 7630 pg/ml in April 1990 and gained 15 lb. in 2.5 months. On May 31, 1990 she gave birth to a healthy pup. The pup was nursing within three hours of birth and quickly gained weight. Although the pup had to be separated from its mother for several weeks because of poor fur condition, they have recently been reunited. Both animals are in excellent condition.

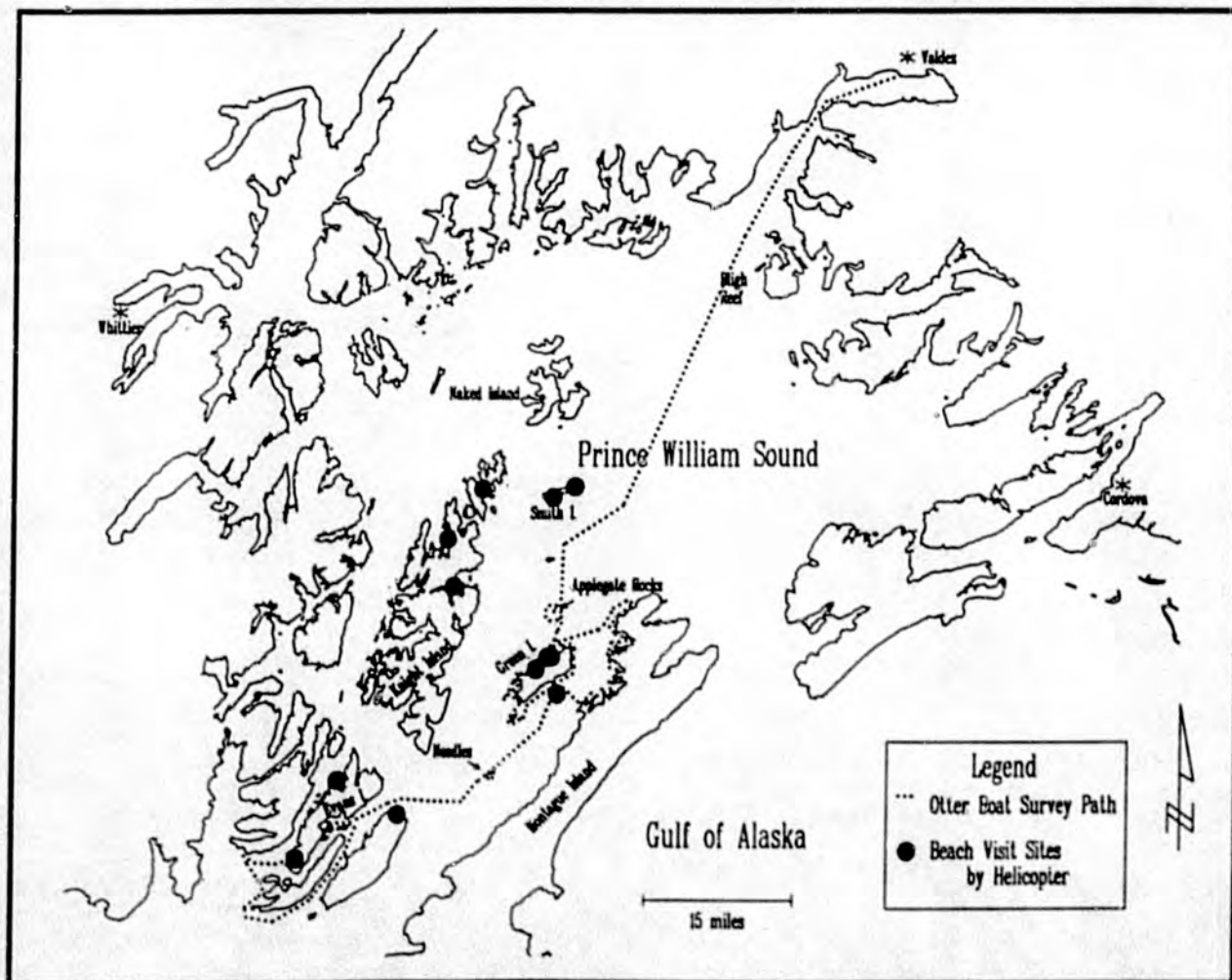
Field Observations of Wild Sea Otters

Approximately 100,000-200,000 sea otters are found throughout the coastal areas of Alaska (Rotterman and Simon-Jackson, 1988). Of these, almost 16,000 animals inhabited areas within the oil

spill zone (DeGange *et al.*, 1990). Currently, we do not know the exact number of otters impacted by the spill. Reliable counts show nearly 900 sea otter carcasses retrieved from the spill area (DeGange and Lensink, 1990) and 357 live animals brought into rehabilitation centers (Williams & Davis, 1990).

The degree of oiling and consequent mortality in wild otters declined early in the spill, paralleling the pattern observed in rehabilitation centers. By May 19, 1989 approximately 70% of the otter carcasses had been retrieved (DeGange and Lensink, 1990). An estimated 80% of these mortalities were attributed to exposure to oil. After the initial phase of the spill, the major concerns for wild otters were the possibility of fur contamination from residual oil on the water or beaches and toxicoses from

Field sites visited in Prince William Sound (below) and along the Kenai Peninsula (next page). Site selection was based on primary capture points for oiled sea otters during 1989 (Williams and Davis, 1990).



eating contaminated prey. A toxic response from direct contact with the oil was unlikely because most of the volatile petroleum hydrocarbons had dissipated within days of the spill (Neff *et al.*, 1990).

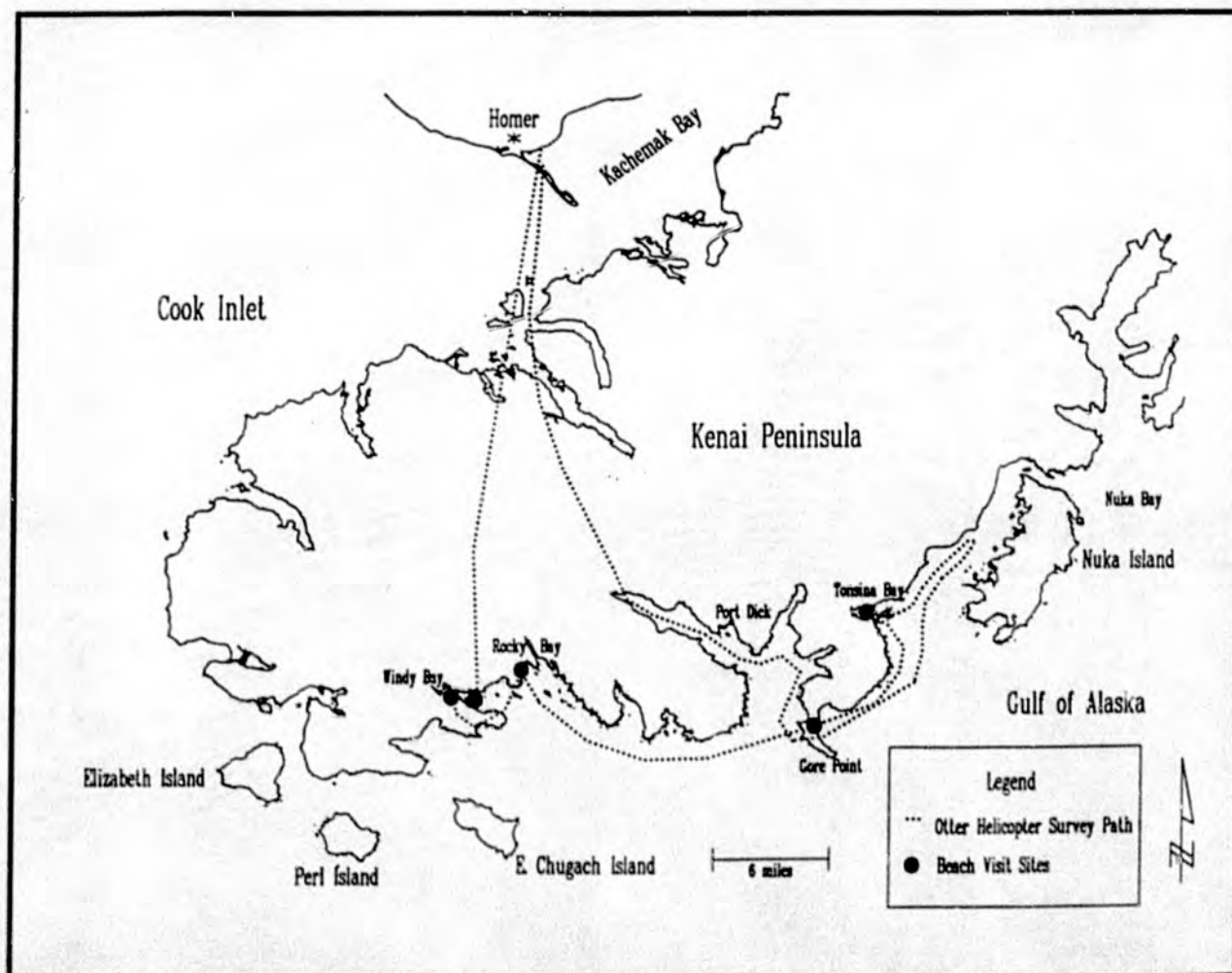
Field studies were conducted to determine the potential for continued contamination of wild sea otters. In early August, we examined areas of Prince William Sound and the Kenai Peninsula that were primary capture sites of oiled otters following the spill (see maps). These sites, which we visited by boat and helicopter, included Rocky Bay (40+ otters captured), Windy Bay (65 otters), Tonsina Bay (27 otters), Green Island and Applegate Rocks (40+ otters) and Evans Island (17 otters captured). The observation period for each was less than a day, therefore this is not considered an exhaustive otter count. In addition, we examined Sleepy Bay, a site of persistent heavy oiling and active cleanup activ-

ity during 1989 and 1990.

Each field site was evaluated in terms of its potential for contaminating sea otters. General beach condition was inspected visually for the presence and type of oil on the substrate. The presence of invertebrates and kelps was considered indicative of beach recovery. Evidence of sheen oil on the water surface was also determined.

Otters and Pups

We observed sea otters of all age classes (adults, juveniles, and pups) at many of the field sites in Prince William Sound and along the Kenai Peninsula. Other marine mammals, including Steller sea lions, harbor seals, killer whales and humpback whales were also seen in these areas. In this study, the largest concentration of otters (more than 150 adults and several pups) was found around Montague



Island. We saw 43 individuals in La Touche Passage, more than 80 otters, including juveniles and mother-pup pairs, near Green Island and Applegate Rocks, and small groups of otters along the Kenai Peninsula (including eight adults and two pups in Windy Bay and a raft of 40 animals by Gore Point). Few otters were seen in areas around the northern islands of Prince William Sound (i.e., Herring Bay, Smith Bay, Prince of Wales Passage, Naked Island). We did not see any otters in Tonsina Bay, although other investigators have observed them at this sight.

The sea otters sighted within the spill area appeared healthy. All animals were active and displayed typical behaviors. When approached by boat, the animals slowly swam away. If observed from the shore, the otters groomed, dove, and rested on the water's surface. In general, the coats of the animals appeared water repellent; dark areas indicative of saturation were not observed.

Suitability of the Habitat for Sea Otters

Sea otters forage along shore areas and feed on a variety of bottom dwelling invertebrates, but rarely on fish in Prince William Sound (Estes, 1980). The otter's diet reflects local prey abundance; in Alaska, prey items include sea urchins, mollusks, crustaceans, and some epibenthic fishes. Because many of these prey items are located in shallow areas and are known to accumulate petroleum hydrocarbons (Neff, 1979), exposure to crude oil or toxic hydrocarbon metabolites through ingestion of tainted food was a concern for wild sea otters. Current evidence, however, indicates that contamination of invertebrates was limited to isolated areas of Prince William Sound, the Kenai Peninsula, and Kodiak (Varanasi *et al.*, 1989). In a previous study edible tissue samples of mollusks from a tour of 13 sites had levels of aromatic hydrocarbons in excess of reference samples taken from Angoon, an Alaskan village



Many of the prey items for sea otters are evident in the Prince William Sound area.

outside the spill area. Three of these four sites (Kodiak, Chenega Bay, and Old Harbor) appeared to have been contaminated by spilled or discharged marine fuels from boat traffic in the village areas. Windy Bay mollusks, which appeared to have been contaminated by the Exxon Valdez spill, showed light aromatic hydrocarbons up to 16,000 ppb and heavy aromatics up to 2,500 ppb (Varanasi, 1989). However, even these levels of contaminants, the highest measured in the Subsistence Food Safety Study, are not considered a serious health risk for human consumption (USFDA, 1990).

It is difficult to predict whether these isolated areas of contaminated prey pose a significant threat to wild sea otters. We do not know if otters can detect petroleum hydrocarbons in food or if they will avoid contaminated prey. Nor do we know the amount of contaminated prey that would have to be ingested before a toxic response occurs. In view of these uncertainties and isolated patches of oil, it is unlikely that a large segment of the Alaskan sea otter population would locate and digest harmful quantities of contaminated prey.

Although most of the harmful components of the oil dissipated within days of the spill (Neff *et al.*, 1990), residual oil on beaches or on the water

surface could be detrimental to the fur of sea otters. Previous studies have shown that weathered oil does not have as great an impact on insulation as fresh crude (Williams *et al.*, 1988) because it is more viscous, remains on the tips of the hair, and is less disruptive to the insulating air layer. Likewise, the absence of hypothermia in lightly oiled sea otters at rehabilitation centers indicates that sheen oil is less disruptive to insulation than fresh oil (pers. obs.).

For most of the sites visited, surface oiling was limited to isolated areas of beach. Usually, traces of oil had hardened in thin layers on rock, sand, or pebbles. We occasionally found spots of tar between rocks, but we saw little evidence of oil sheens

on the water. This situation contrasts with conditions on capture beaches in 1989, when fresh oil or thick layers of mousse covered the beaches to upper tidal lines and sheens of oil were often observed on the water surfaces near heavily oiled shores.

In 1990 we surveyed two beaches, Herring Bay and Sleepy Bay, that were exceptions. At these worst case sites, we saw areas of standing oil and some sheening in the water. Although sea otters were not seen near these beaches, the potential for contamination of their fur does exist. However, neither USFWS nor the cleanup crews at these beaches reported sightings of oiled sea otters.



We observed many other mammals, including these steller sea lions, during the field investigations.

Prognosis for Captive and Wild Sea Otters

Behavioral, medical, hematological, reproductive, and toxicological parameters indicate that it is possible for otters to recover from many of the initial effects of oil exposure. Except for one pup, the captive otters recovered from many of the effects of exposure within 3 - 4 months. Coat condition, a critical factor for sea otters, was restored to normal water repellency within one month of thorough cleaning. Petroleum hydrocarbon levels that were comparatively high initially, declined to insignificant levels after twelve months of captivity. Consequently, the current prognosis for the captive animals is good.

Because the otters in this study received veterinary care and ad libitum food, it is difficult to extrapolate to animals in the wild population. Preliminary results from radio-instrumented animals indicate that rehabilitated otters are initially vigorous following release into the wild. Mortality increased during winter months indicating a susceptibility to environmental factors (Monnett *et al.*, 1990). Before conclusions can be drawn, however, further research is needed to determine the relationship between the degree of oiling of otter fur and survivorship in free-ranging sea otters.

Conditions in Prince William Sound and the Kenai Peninsula have improved, in terms of the suitability of the habitat for sea otters. Water column and subsistence fisheries reports, as well as the present study, indicate few traces of oil. In many cases the oil is: 1) inert; 2) limited to isolated shores and prey items; and 3) in a form which poses little threat to sea otters. Large numbers of adults and pups were found in previously oiled areas, and they appear to feed and behave normally. These results suggest that many of the previously contaminated areas are able to support sea otters. With time and further research, we will be able to determine the resiliency of both the sea otter population and its habitat in Alaska.

Acknowledgments

I would like to thank R. Davis for generously providing his field notes. Sea World (San Diego), the Shedd Aquarium (Chicago), the Point Defiance Zoo, and the Vancouver Aquarium provided invaluable information about their Alaskan sea otters; the enthusiasm of T. Goff and J. Robinnette is especially appreciated. J. White, M. Barker, D. O'Connor, and R. Mastracchio reviewed numerous drafts of this manuscript and provided insightful comments. In addition, I gratefully acknowledge the support of Exxon Company, USA who sponsored this research project through the 1989 Sea Otter Rehabilitation Program.

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Table 1

Condition of Captive Sea Otters

Otter #	Coat Condition		Health Status		Weight			Blood Panel		Paraffinic Hydrocarb. in Blood
	Initial	Final	Initial	Final	Initial	Final	% Gain	Initial	Final	TPH (ppm)
Adults										
VA-5 (3-31)	Heavy Oil	Good	Lethargic Emphysema	Normal	35	47	34	Anemia elev. CPK	Normal	ND *
VA-26 (4-1)	Heavy Oil	Good	Emphysema	Normal	32	47	47	elev. WBC	Normal	ND
VA-36 (4-2)	Heavy Oil	Good	Lethargic Diarrhea	Normal	52	54	4	Normal	Normal	ND
VA-51 (4-4)	Not Documented	Good	Emphysema	Normal	30	46	53	elev. WBC, LDH & CPK	Normal	-
VA-115 (4-10)	Light Oil	Good	Fair	Normal	38	52	37	elev. SGPT, LDH & CPK	occasional elev. WBC	-
VA-117 (4-11)	Light Oil	Good	Fair	Normal	62	73	18	elev. WBC	Normal	ND
VA-126 (4-16)	Mod. Oil	Good	Emaciated	Normal	46	56	22		Normal	ND
VA-132 (4-17)	Heavy Oil	Good	Lethargic Diarrhea	Normal	43	52	21	elev. WBC	occasional elev. WBC	-
Pups										
SW-4 (5-1)	No Oil	Good	Thermal Instability	Normal	10	32	220	-	Normal	ND
SW-102 (5-10)	No Oil	Good	Underweight	Normal	13	32	146	Anemia	Normal	ND
SW-106 (5-21)	No Oil	Good	Underweight	Fair	6	32	433	Anemia	Abnormal	ND
SW-133 (6-13)	No Oil	Good	Hypothermic	Normal	6	29	383	Anemia	Normal	ND

* ND = Non Detectable Amounts

CPK = Creatine Phosphokinase

LDH = Lactate Dehydrogenase

WBC = Total White Blood Cell Count

SGPT = Alanine Aminotransferase

TPH = total paraffinic hydrocarbons

Note: TPH measurements were made at 12 months.



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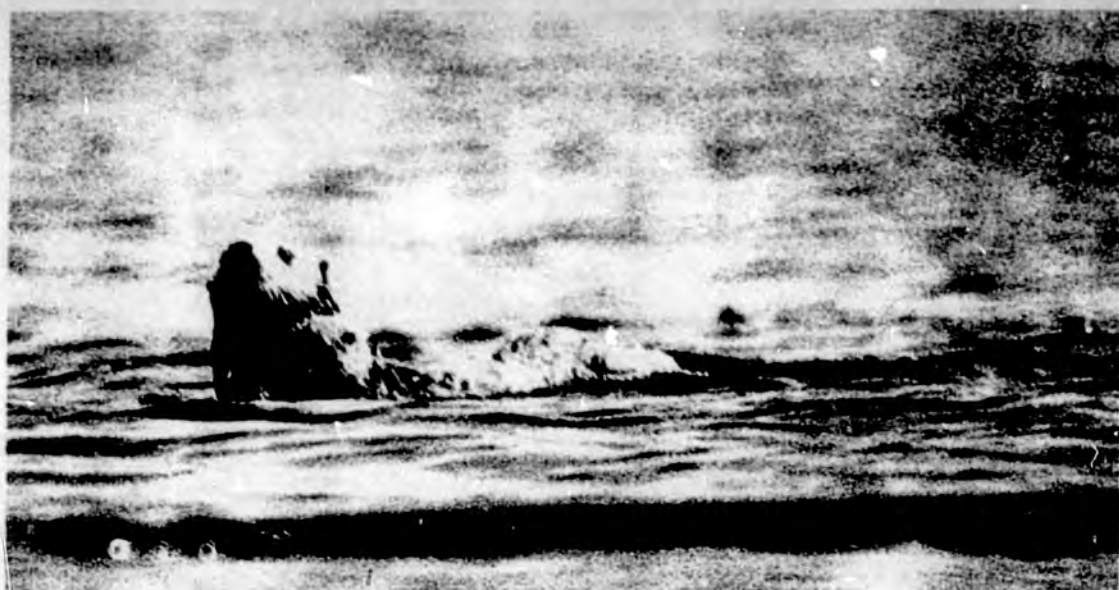
Sea Otters Thrive in Prince William Sound, Alaska



Sea otters are plentiful in the Prince William Sound area. Experts like Terrie Williams and Randall Davis have been working with the area's sea otters since the 1989 oil spill.

February 1991

Sea otter pups and juveniles make up a good portion of the area's population.



Thousands of sea otters inhabit the Prince William Sound area. Hundreds of pups were spotted in 1990.

Thousands of Otters and Pups

More than 16,000 sea otters inhabit the portions of Prince William Sound and the Gulf of Alaska that were impacted by the 1989 oil spill. Regrettably, more than 1,000 otters died at the time of the spill, but

recent observations confirm that the otter population is recovering. Hundreds of pups were spotted in 1990. A female adult otter typically produces a pup every year or so.



The area's sea otters rely on shellfish for food. They consume 25 to 30% of their body weight each day. Government studies conducted after the spill confirm that the area contains ample shellfish supplies safe for humans to eat.

A Diet of Shellfish

The area's sea otters rely on shellfish for food year round. The Sound's supply has helped sea otters recover from near extinction a few decades ago. They are no longer an endangered species in Alaska.

Immediately after the oil spill, there was concern over the area's shellfish. The State of Alaska and the Federal Government conducted extensive studies of all the area's subsistence foods, including shellfish. Their conclusion: ample stocks of shellfish were available and safe for humans to eat.



The majority of Prince William Sound was never oiled in 1989 and oil slicks are no longer on the water's surface.

Clean Water

Sea otters spend virtually all of their lives in and on top of the water. Any significant volume of oil on the surface of the water seriously threatens the otter habitat.

In 1989, oil from the Valdez spill remained on the water's surface only a short time, and only in a portion of Prince William Sound. Extensive tests have confirmed that the spill did not compromise the water column's quality.

Clean Beaches

The 1989 tanker spill impacted less than 20% of the area's shoreline. By the fall of 1990, about 1% of the shoreline still had patches of oily residue on it. The crude oil has "weathered" and lost its toxicity.

Following harsh winter storms and two summers of clean-up operations, Prince William Sound is essentially cleansed of oil from the Valdez spill.

Resilient Sea Otters

A sea otter, more than any other marine mammal, is vulnerable to oil spills because of its fur and lifestyle. Drs. Davis and Williams believe this animal's resiliency should not be taken for granted and everything reasonable to prevent another spill from happening should be done.

Fortunately, the evidence suggests that sea otters in the Prince William Sound area are thriving. Nearly two years have passed since the oil spill, and sea otters are plentiful throughout the region.

The evidence suggests that sea otters in the Prince William Sound area are thriving.



Drs. Terrie M. Williams and Randall W. Davis managed Exxon's Sea Otter Rescue and Rehabilitation Program following the 1989 Valdez oil spill. Because of those efforts, nearly 200 wild sea otters were treated and returned to Prince William Sound. Dr. Williams is currently a Research Physiologist with the Naval Ocean Systems Center in Hawaii. Dr. Davis is head of the Department of Marine Biology at Texas A&M University. In addition, they co-direct International Wildlife Research.

If you are interested in more details about the Prince William Sound sea otters, please write to: Exxon Company, U.S.A., Otters, P.O. Box 2180, Houston, Texas, 77252-2180 for a copy of two technical reports: "Evaluating the Long-term Effects of Crude Oil Exposure in Sea Otters: Laboratory and Field Observations" by Terrie M. Williams, Ph.D.; and "Advances in Rehabilitating Oiled Sea Otters: The Valdez Experience" by Randall W. Davis, Ph.D.



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The *Exxon Valdez* oil spill: Initial environmental impact assessment

Part 2 of a five-part series



FIGURE 1

(a) Smith Island, Prince William Sound, April 1989

Alan W. Maki
Exxon Company, U.S.A.
Anchorage, AK 99519-0409

The March 24, 1989, grounding of the *Exxon Valdez* on Bligh Reef in Prince William Sound, Alaska, was unprecedented in scale. So too was Exxon's response to the oil spill and the subsequent shoreline cleaning program, including the employment of more than 11,000 people, utilization of essentially the entire world supply of containment booms and skimmers, and an expenditure of more than two billion dollars. In the days immediately following the *Valdez* spill, Exxon mobilized a massive environmental assessment program. A large field and laboratory staff of experienced environmental professionals and in-

ternationally recognized experts was assembled that included intertidal ecologists, fishery biologists, marine and hydrocarbon chemists. This field program to measure spill impacts and recovery rates was initiated with the cooperation of state and federal agencies. Although the agencies subsequently foreclosed cooperation in most of these studies because of litigation concerns, this comprehensive assessment program continues today. Through the end of 1989, this program has resulted in well over 45,000 separate samples of water, sediment, and biota used to assess spill impacts.

It is the intent of this paper to provide initial observations and preliminary conclusions from several of the 1989 studies. These conclusions are based on factual, scientific data from studies designed to objectively measure the extent of the impacts

from the spill. Data from these studies indicate that wildlife and habitats are recovering from the impacts of the spill and that commercial catches of herring and salmon in Prince William Sound are at record high levels. Ecosystem recovery from spill impacts is due to the combined efforts of the cleanup program as well as natural physical, chemical, and biological processes. From all indications this recovery process can be expected to continue.

Design of the assessment program

In early 1990 *Environmental Science & Technology* completed a four-part series on the state of the science of ecotoxicology and ecological risk assessment (1-4). This series reviewed the development and current regulatory applications of the ecological risk assess-



FIGURE 1
(b) Smith Island, June 1990

ment paradigm based on sequential comparisons of environmental fate (chemistry) data and biological effects data. Much of this literature is the basis for the Technical Information Documents (5, 6) being used by the regulatory agencies and supports the "Type B" natural resource damage assessment rules promulgated under Section 301 (C) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

The environmental fate-and-effects approach also forms the backbone of the *Exxon Valdez* environmental impact assessment program as discussed in these pages. Each of the studies was carefully designed to accurately measure hydrocarbon concentrations in the environment and within specific biological components as well as measure observed biological effects at individual trophic levels. For each program, environmental fate data complemented effects data to ensure that a fate-and-effects correlation could be developed to assess the likelihood of impacts.

Shoreline habitat

As a result of the grounding of the *Exxon Valdez*, some 258,000 barrels of crude oil were released into the water. Winds of more than 70 mph on the third day after the grounding rendered con-

tainment of oil on the water impossible, with the result that shoreline habitat in the southwestern segment of Prince William Sound was impacted. During the next few weeks more than 1100 miles of shoreline in south-central Alaska were impacted by oil to varying degrees (Table 1). These shoreline areas represented the habitat most obviously impacted by the spill where floating oil and mousse (oil-water emulsion) were washed ashore and deposited in intertidal areas. Indeed, it was these areas that were the focus of the two-billion-dollar cleanup program during 1989 and 1990.

It is important to point out that, at the very worst, slightly more than 10% of the shoreline habitat in Prince William Sound and the Gulf of Alaska was impacted by oil, thus leaving 85-90% of the regional shoreline untouched by oil (Table 1). Predictably, the percentage of impacted areas dropped significantly to approximately 1% of the shoreline areas in 1990 as a result of both the cleaning program and natural weathering. This effect can be seen most dramatically in the accompanying photographs of heavily impacted shoreline in 1989 and the comparatively clean state in the spring of 1990 (Figure 1).

Shoreline oiling data are the results of the 1990 spring shoreline assessment wherein 20 separate teams, each consist-

ing of state of Alaska agency, and Exxon representatives, assessed more than 120 miles of shoreline in Prince William Sound and the Gulf of Alaska. A total of 1,000 pits were assessed had no oil retained in < 10 cm. In addition, 5071 pits were dug to determine the extent of subsurface oiling. Subsurface oil (oil deeper than 10 cm) was found in 733 (14%) of the pits dug. The locations recommended for 1990 summer cleaning were widely scattered and generally confined to short lengths of shoreline; all identified areas received attention during the summer.

Biota. The shorelines of southern Alaska are predominantly large rocks, boulders, and cobbles with less than 10% of the area characterized as soft substrate. This rocky intertidal zone is an extremely harsh habitat. Plants and animals living there have evolved to cope with a highly unstable substrate, extremely forceful breaking waves, and wide seasonal and diurnal ranges in photoperiod and temperature. As a result, many of these areas have naturally low species density and diversity.

Barnacles, mussels, and rockweed (*Fucus*) are the best indicator species for visually estimating the biological condition of these intertidal habitats. They are good indicators of trends in recruitment

and loss caused by oil or other natural phenomena. In order to assess spill impacts on shorelines, these species and the intertidal communities in Prince William Sound and the Gulf of Alaska have been sampled via counts of species density, percent cover, species diversity, and photographic surveys of intertidal biota.

Results from the shoreline surveillance program indicate that although species densities were lower on heavily oiled shorelines, and high local mortalities occurred where oil coverage exceeded 90%, the species compositions of communities are similar to those that would be expected on comparable shorelines in the absence of oil. Even where oiling remains in sheltered, soft substrate areas, the spring and summer growing season of 1990 confirmed that continued recovery was under way (Figure 2). Thus, intertidal invertebrates and plants do survive on oiled shorelines, a point that supported spill researchers' conclusions that further extensive, intrusive shoreline cleaning efforts were unwarranted (7).

This recruitment trend also has been observed in several studies of other spills worldwide that showed that shoreline biota recovered in impacted areas within a few years after the spill (8).

Shoreline field-monitoring data support the following conclusions:

- The amount of oil remaining on the shoreline has continued to decrease since the summer of 1989. There are few oiled shores remaining.
- The impact to intertidal communities was a decrease in the number of individuals of each species and a change in the species composition of the communities. The intertidal communities are intact.
- Intertidal plants and animals were found settling and surviving on shorelines throughout Prince William Sound and the Gulf of Alaska throughout the 1989 and 1990 growing seasons.
- Even where residual oil remains on a few shorelines, biological recovery is taking place.

Water quality

Within six days of the spill, Exxon initiated an extensive water quality sampling program in Prince William Sound to help assess possible impacts on the marine biological community by measuring hydrocarbon concentrations in the waters of the Sound. Water samples were collected from March through October 1989 at 35 offshore locations.

More than 2300 water quality samples have been analyzed to date. Figure 3 is a plot of the average polycyclic aromatic hydrocarbon (PAH) concentrations through-

TABLE 1
Alaskan coast impacted by Exxon Valdez oil

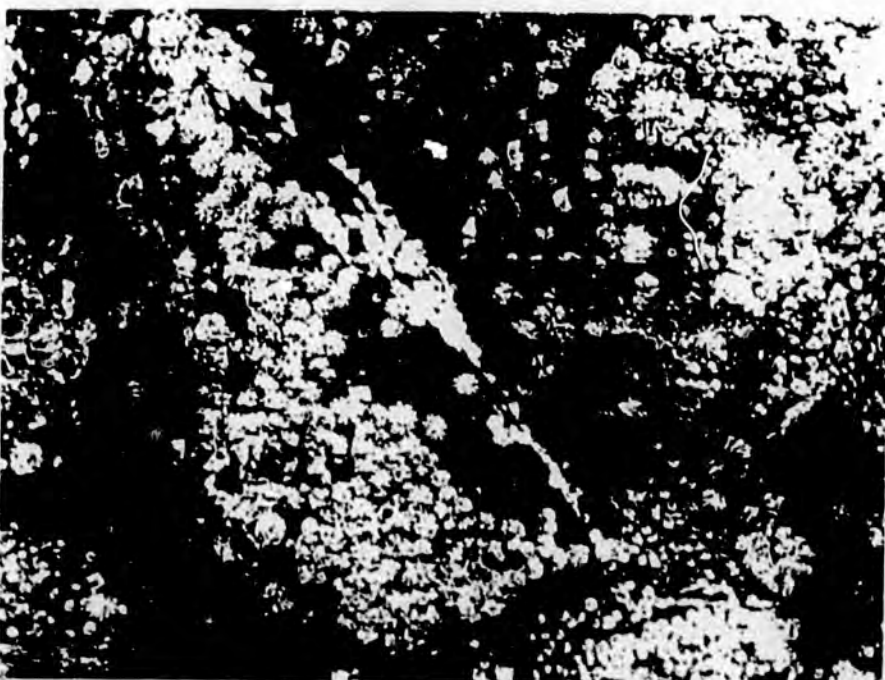
Area	Total coast (miles)	Oil-impacted coast, May 1989 (miles)	Total coast impacted, May 1989 (%)	July 1990 oil-impacted coast (miles) ^a	Total coast with oil, July 1990 (%)
Prince William Sound	3061	357	11.6	91.5	3.0
Gulf of Alaska	6345	732	11.5	24.1	0.4
Total (miles)	9406	1089		115.6	

^aJoint Exxon/Agency Spring Shoreline Assessment Teams (SSAT) report. Wide (>6 m), moderate (3-6 m), and narrow (<3 m) oiling widths combined.

FIGURE 2
Biological growth in Prince William Sound, spring and summer 1990



Grass sprouting from sediment containing residual oil



Barnacle growth on oil-stained rock

out the year. The three curves represent the averages of different sites. The solid line represents the three sites with the highest concentrations. These are three bays that were heavily oiled. Note that the average of these three worst bays peaked at only 7% of the Alaska state water quality standard. The average of all primary sites has a maximum value of about 1/50th of the state allowable limit for aromatics in water (9).

These data all confirm that average hydrocarbon concentrations measured in the water column for the more toxic components have consistently been well below state of Alaska standards and are 10–1000 times lower than levels lethal to plants and animals living in the water column, including commercially important fish species.

Fisheries

Pacific herring. Annually, millions of herring enter Prince William Sound to spawn in early April. This spawning period determines the commercial herring fishing season which had a 1988 value of \$12 million. The *Valdez* spill occurred approximately three weeks prior to the peak of the Pacific herring spawn. Concern regarding potential impacts to the herring resulted from the fact that herring deposit their eggs on kelp in the intertidal and shallow subtidal zones in Prince William Sound.

Results of aerial surveys flown by Alaska Department of Fish and Game field biologists confirm that both 1989 and 1990 spawning activity was comparable to historical averages for the years immediately preceding the spill (Figure 4). These data provide convincing evidence that herring spawning activity has been neither impaired nor delayed during the period when highest potential existed for exposure to spilled oil.

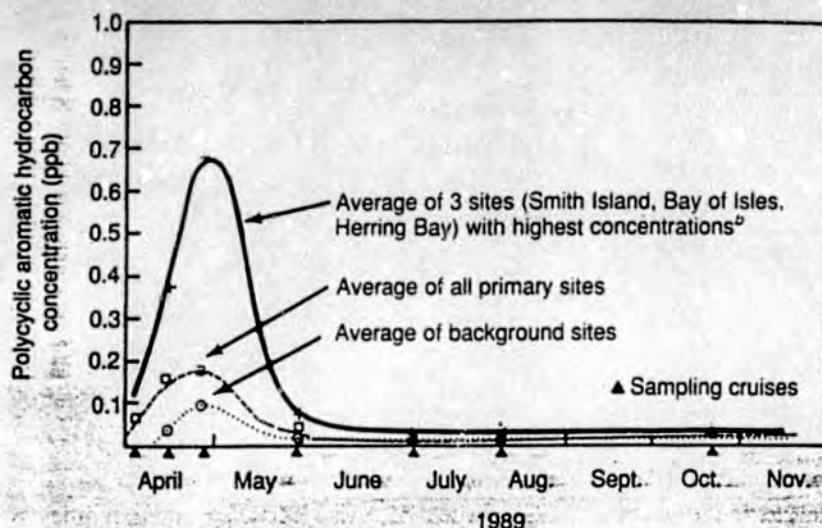
These conclusions were further substantiated by the results of the 1990 commercial herring fishing season wherein 8300 tons of herring were harvested during the 20-minute season opening on April 12th—an all-time record catch for the sac roe fishery. Record harvests were also achieved in the gill net and wild roe-on-kelp fishery seasons, thus minimizing concerns over long-term impacts on this important commercial fish species.

Pink salmon. The Prince William Sound salmon harvest is dominated by pink salmon and was worth approximately \$63 million in 1988. Data collected during the critical life stages of the pink salmon population show no significant oil-related effects.

An extremely healthy and vigorous zooplankton bloom supported the spring 1989 release of more than 600 million fry from the commercial fish hatcheries of Prince William Sound. Outmigrating

FIGURE 3

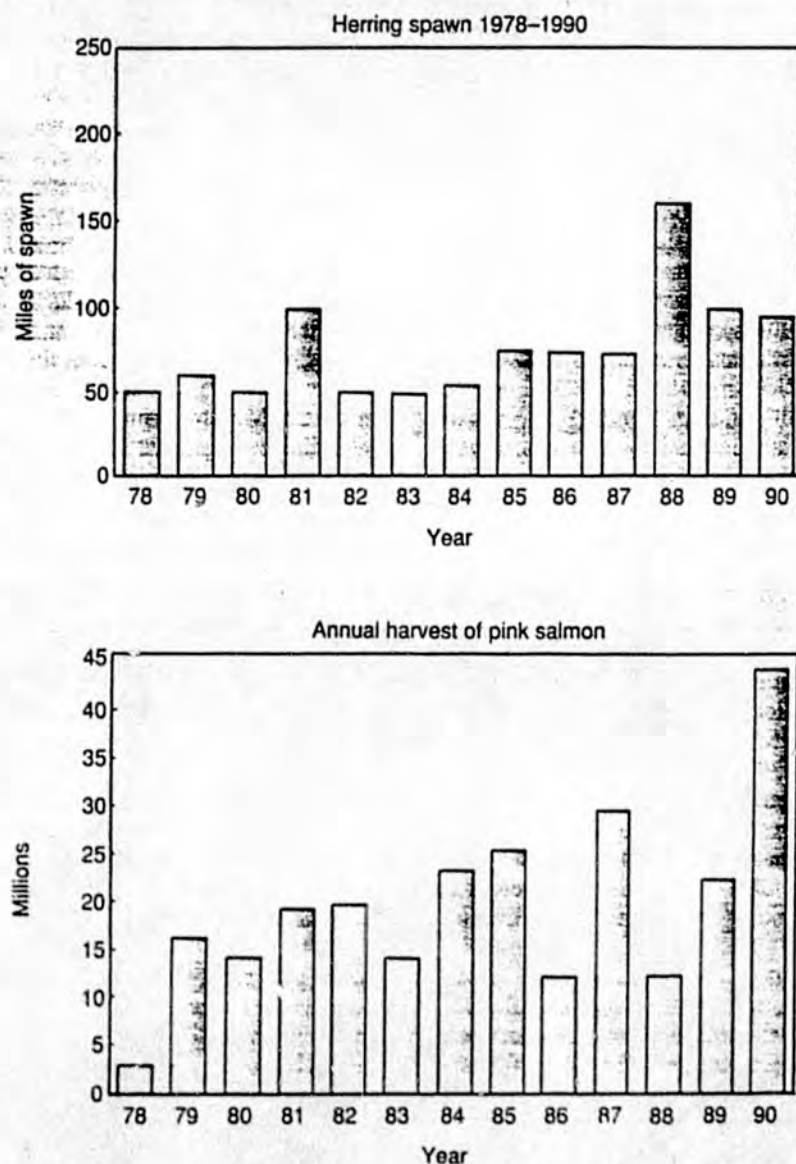
Average polycyclic aromatic hydrocarbon concentrations for Prince William Sound water^a



^aState of Alaska criterion for petroleum aromatics in water is 10 ppb.
^bPeak is 7% of state allowable limit.

FIGURE 4

Prince William Sound fish production



fry and juveniles in 1989 were apparently not impacted, and many juvenile salmon were observed in both oiled and unoiled nearshore areas. Similarly, field experiments with caged juveniles noted no differences in survival between oiled and unoiled sites. When the 1989 adults returned to spawn in the streams flowing into Prince William Sound, several streams had abnormally large numbers of returning fish. Also, no differences were evident in the spawning utilization of streams in oiled areas versus unoiled areas. Subsequent experiments in the fall with the incubation of eggs buried in gravel at several oiled and unoiled sites demonstrated similar survival and hatching rates between these sites, thus minimizing concerns over oil effects on this sensitive life stage.

Pink salmon have a short two-year life cycle. In the summer of 1990, those young salmon that left their native streams in April 1989, just after the spill, returned to spawn. The reported harvest through September 12, 1990, was 35.1 million fish taken, with an additional 8.9 million taken from hatchery stocks. This makes the 1990 commercial catch an all-time record, ahead of the 1987 record level by about 14 million fish and 163% ahead of the pre-season forecast for cumulative harvest. This strong run consists of both hatchery and wild-stock production (Figure 4).

In summary, there have been no indications of any significant pink salmon kills or effects on spawning activity related to oil exposure.

Shellfish and subsistence fisheries. Shellfish and crustaceans constitute a much less significant but still important part of Alaskan commercial, subsistence, and recreational fisheries. Several species of clams, mussels, crabs, and shrimp occupy the spill-impacted areas. Following the spill, a cooperative program was initiated between the Alaska Department of Fish and Game, the National Oceanic and Atmospheric Administration (NOAA), Exxon, and the subsistence communities to examine subsistence food safety in the spill-impacted areas. As of July 1990, more than 1300 samples of fish and shellfish have been collected in seven sampling cycles representing 23 species of fish and shellfish from 13 subsistence resource areas. They are being tested for aromatic hydrocarbons, the toxic components of crude oil most likely to be assimilated by shellfish.

The results of the chemical analyses received from the NOAA Seattle laboratory are very encouraging (Figure 5). Contaminant levels in all the fish and most shellfish were extremely low compared to data for fish and shellfish from a control site at the village of Angoon, outside the spill-impact-

ed area. Except for shellfish taken from Windy Bay and from Kodiak Harbor, all food resources sampled showed safe hydrocarbon levels.

A Toxicological Expert Committee consisting of representatives of the Food and Drug Administration, the National Institute of Environmental Health Sciences, NOAA, the National Marine Fisheries Service, the Alaska Department of Public Health, and various university and industry toxicologists reviewed the data and filed a consensus report. The committee concluded that finfish from anywhere in the study area are safe to eat in unlimited quantities, and except for those taken from obviously oiled shores, shellfish are also safe to eat (10).

Wildlife: Initial impacts

Some 36,000 bird mortalities were documented between March and September 1989. Although some of these were natural mortalities, no doubt exists that a significant number were caused by the spill. More than 1000 sea otter and 153 bald eagle mortalities were initially attributed to the spill. Although there was an extensive effort to recover dead birds and animals, actual mortalities were likely higher. When the above mortality figures are compared with total populations in the spill-impacted area—more than 10,000,000 sea birds; more than 30,000 sea otters; and 5000 eagles—indications are that recolonization has been rapid and robust, as it has been following other spills throughout the world (8).

Furthermore, extraordinary measures were taken to rescue and care for birds and otters that were impacted. From the period of March through September 1989, Exxon organized the largest and most comprehensive bird and sea otter rescue and rehabilitation programs ever attempted. Facilities for the holding, cleaning, and care of oiled birds and otters were built at Valdez, Seward, Homer, Kodiak, and Anchorage. During the program, more than 140 boats and 5 aircraft were used to retrieve oiled birds and otters from remote locations throughout Prince William Sound and the Gulf of Alaska.

Some 71 species of birds were handled during the six-month program. More than 1600 birds were brought in live for treatment with a release rate for the sea birds of 50%. Given the time of year of the spill, the climate, the remoteness of the site, and the logistics, this survival and release rate compares favorably with the 30–60% range of release rates seen in other spills. At its maximum, the bird program employed some 400 bird rescue personnel; this effort cost more than \$25 million.

Teams were hired to work in Prince

William Sound and Kodiak to collect eagles from heavily impacted areas to determine the need for potential rehabilitation. These capture teams caught 114 eagles; only 16 required treatment. (An additional 23 eagles caught by others not associated with the capture teams were also treated).

The staff of the otter centers grew to more than 320 specialists and volunteers at all three locations. From March 30 until September 15, 357 sea otters were treated and held at the centers; 223 (62%) were rehabilitated and released or placed in aquariums. Expenditures for this effort exceeded \$18 million.

Wildlife monitoring program

As noted, in spite of the best efforts by all parties, many birds died. To assess overall population-level impacts, comprehensive wildlife monitoring programs were initiated after the spill and are ongoing.

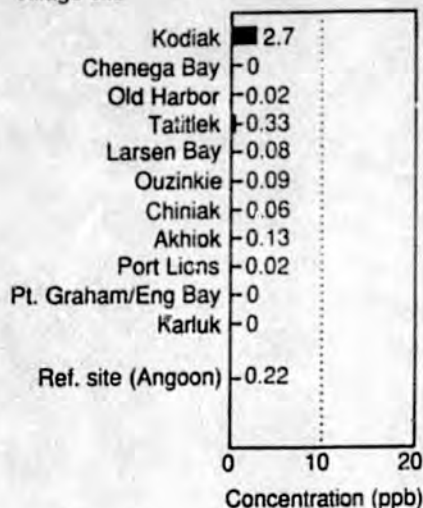
Bird monitoring. Results of Exxon and agency winter, spring, and summer wildlife monitoring programs are very encouraging. There have been no documented reports of oil or sheens affecting populations of birds or marine mammals, and there have been no confirmed mortalities attributable to oil since September 1989. Additionally, wildlife observations in Prince William Sound indicate that significant numbers of birds from 45 different species occupy previously heavily oiled areas and appear to be unaffected by existing conditions. Species diversity and density are similar for both oiled and unoiled areas.

The findings of the winter wildlife population surveys are most encouraging. These surveys of oiled areas in Prince William Sound show that bald eagle sightings have consistently increased since the summer of 1989. Data from cooperative U.S. Fish and Wildlife Service eagle surveys throughout the summer of 1990 indicate that 1031 of 2030 nests (51%) in the spill area were active and that 61 of 75 previously active nests (81%) in Prince William Sound cleanup sites produced an average of 1.4 eaglets per nest, thus matching historical productivity statistics for this area. It is recognized these data do not allow definitive statements of eagle population dynamics, but they do provide conclusive evidence that animal life is present in habitats previously impacted by the oil spill.

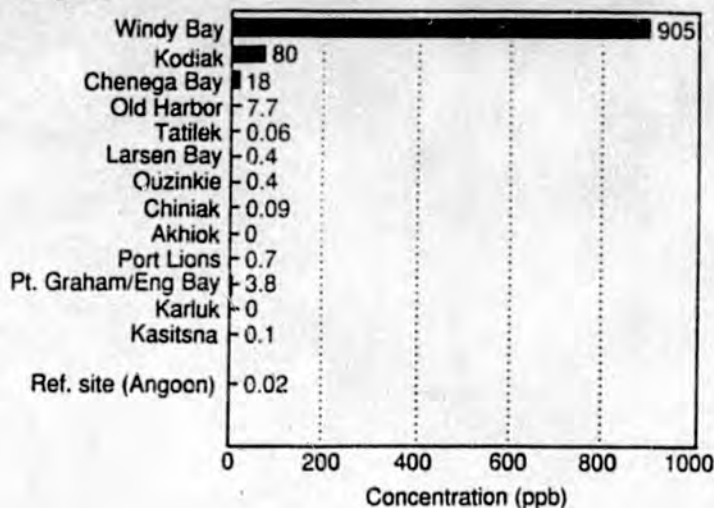
Mammal monitoring. Results of the winter mammal monitoring program indicate the presence and successful reproduction of mink and river otters in both oiled and unoiled bays of Prince William Sound. Sea otters are present in all areas in apparently equal numbers in oiled and unoiled bays.

FIGURE 5
Concentrations of aromatic hydrocarbons^a

In salmon
Village site



In mussels and clams
Village site



^aPrince William Sound, lower Cook Inlet, Kodiak.

Although census results of sea otters often vary widely, the Prince William Sound population has been generally estimated at 5000 to 6000 (11), with some recent estimates being as high as 9000. The Prince William Sound population was believed to be less than 50 individuals when commercial harvesting of this species ended in 1911. The population has increased very rapidly in recent years, and field surveys of 550 miles of oiled shorelines counted more than 350 sea otters. This survey covered about one-sixth of the total Prince William Sound shoreline. It indicates that otter populations are approaching pre-spill densities (11) and provides convincing evidence of sea otter recolonization of previously heavily oiled areas.

In summary, the monitoring data for mammals indicate that environmental conditions have improved enough that the spill should have no further substantive impacts on wildlife. Recovery is well under way.

Conclusions

A recently published Congressional Research Service report (12) carefully reviews the extent of environmental impacts from several previous oil spills worldwide and concludes that "To date, pollution from offshore petroleum activities has not appeared to be a significant threat to the survival of various species ... Despite short-term media attention to the catastrophic nature of major spill events, the chemicals contained in petroleum have long been part of the marine environment and physical impacts are likely to be temporary in the dynamic natural flux of the coastal environment."

Available data to date for the Valdez spill are consistent with the observations made in this report. Samplings of petroleum aromatic hydrocarbon concentrations in the waters of Prince William Sound clearly demonstrate that average levels have remained well below exposure levels known to cause acute and chronic effects to sensitive aquatic life. Field counts of plants, fish, and mammals from throughout the spill area provide convincing data that wildlife species are surviving and reproducing, thus confirming that biological recovery is rapidly taking place.

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NATURAL RECOVERY OF COLD WATER MARINE ENVIRONMENTS AFTER AN OIL SPILL

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by

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CONTENTS

INTRODUCTION AND SUMMARY OF FINDINGS.....	1
SCOPE AND OBJECTIVES.....	5
BASIC CONCEPTS.....	5
WHAT IS MEANT BY CLEAN?	5
WHAT IS MEANT BY RECOVERY?.....	7
Recovery of the Use of Resources.....	7
Nature of Resources.....	7
Fisheries.....	7
Tourism.....	8
Seaweed Harvesting	8
Biological Recovery Processes	9
Soft Substrata.....	9
Hard Substrata.....	9
Natural Fluctuations	10
Natural Change and Impact Assessment	10
A Working Definition of Ecological Recovery	16
COLD WATER ECOSYSTEMS.....	17
PHYSICAL AND CHEMICAL BEHAVIOUR OF SPILLED OIL.....	17
NATURAL CLEANING	19
PHYSICAL REMOVAL BY NATURAL PROCESSES.....	19
CHEMICAL AND BIOLOGICAL DEGRADATION.....	20
Chemical Degradation.....	20
Biological Degradation.....	21
Microbial Degradation.....	21
Other Pathways	22
NATURAL RECOVERY	23
BIRDS.....	23
Losses of Seabirds from Oil	23
Other Causes of Mass Seabird Mortality	24
Population Effects.....	25
Cleaning and Rehabilitation.....	27

Polar Conditions.....	27
FISHERIES.....	27
Interference.....	28
Tainting.....	28
Sublethal Effects.....	29
Experience in Oil Spills.....	30
SEA MAMMALS.....	31
Effects of Oil.....	32
Avoidance of Oiled Waters.....	32
Casualties in Oil Spills.....	33
PELAGIC ENVIRONMENT.....	33
Plankton.....	33
Laboratory Studies.....	34
Experiments with Large Enclosures.....	34
Experience with Oil Spills.....	35
BENTHIC ENVIRONMENT.....	36
Littoral Zone (Intertidal Zone).....	36
Sublittoral Zone (Subtidal Zone).....	38
ACKNOWLEDGMENTS.....	45
TABLES.....	46
REFERENCES.....	62
APPENDICES.....	89
A. COLD WATER ECOSYSTEMS.....	89
B. PHYSICAL AND CHEMICAL BEHAVIOUR OF SPILLED OIL.....	93
C. EFFECTS OF OIL ON BIRDS.....	103
BIOGRAPHICAL SKETCHES OF THE AUTHORS.....	105
GLOSSARY.....	107

INTRODUCTION AND SUMMARY OF FINDINGS

This review of the published literature examines natural cleaning and natural recovery of ecosystems and biological communities following oil spills in cold water regions of the world. The scientific literature permits generalisations to be drawn; but oil spills in exceptional circumstances may produce exceptional effects. In a number of cases, long-term studies of recovery processes are incomplete, and recovery time scales suggested involve some extrapolation.

The following is a list of major findings from our review, grouped according to the primary subject areas of the paper.

BASIC CONCEPTS

- Consideration of the overall, long-term impact of a particular spill must take into account the relative proportions of oiled- and unoiled-habitats in the area of interest; and, in the case of oiled habitats, the relative proportions of different habitat types. Some areas may have a high percentage of habitats likely to recover relatively quickly, whereas other areas may have a high percentage of habitats likely to recover more slowly.
- For many cases, recovery of the availability of human services of a system impacted by oil is not closely related to biological recovery and is generally more rapid than biological recovery.
- Current evidence indicates that hydrocarbons are present in all environments. They originate from both natural and human sources and serve to define background levels of petroleum hydrocarbons.
- Clean, in the context of an oil spill, is defined here as the return to levels of petroleum hydrocarbons that have no significant detectable impact on the function of the ecosystem. The size of the ecosystem is obviously an important consideration. It is not microscopic, but is large enough to include the major plant and animal communities. Practical application of this definition requires taking into account the relative proportions of oiled- and unoiled-habitats. It does not necessarily require a return to some pre-existing background level or the complete removal of petroleum hydrocarbons from the environment.
- Recovery of an ecosystem damaged by petroleum hydrocarbons begins as soon as the toxicity or other adverse property of the oil has declined to a level that is tolerable to the most robust colonising organisms. Recovery processes can begin in the presence of residual oil.
- Recovery of an ecosystem is marked by the re-establishment of a healthy biological community in which the plants and animals of the community are functioning normally. It may not have the same composition or age structure as that which was

present before the damage and will continue to show further change and development. It is difficult or impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have developed in the absence of the spill.

- Ecosystems are in a constant state of flux due to natural causes. These fluctuations can be as great as, or even greater than, those caused by the impact of an oil spill.

NATURAL CLEANING

- Most of the toxic components in a fresh oil spill on the surface of the sea rapidly evaporate. After evaporation, these toxic components disperse into the atmosphere and are rapidly diluted to background levels. Most of the remaining toxic components that did not evaporate, dissolve and disperse in the water column to low concentrations.
- Generally, the higher the aromatic content of an oil, the higher the toxicity. Weathered crude is less toxic than fresh crude because most of the toxic components have evaporated. Most of the toxic compounds are readily degradable.
- Oil concentrations in the water column below oil slicks are very low.
- The persistence of oil slicks on the sea surface is dependent upon the type of oil spilled and sea state conditions. Some slicks can be removed by natural processes within a few days. Other oils can form stable, highly viscous emulsions (mousses), which may persist for weeks or months in the open ocean. Eventually these slicks will form tarballs that are relatively harmless to biological systems.
- Microbial degradation is an important process in the eventual disappearance of oil from the marine environment. Degradation rate is controlled by oxygen and nutrient availability, temperature, chemical composition and surface area of the oil, and in some cases the activities of other organisms.
- Degradation is oxidative, and therefore the rate is reduced when oxygen concentrations are low, as is sometimes the case in fine sediments.
- Although some oxidation products resulting from biodegradation or photolysis are toxic, their rates of generation are slow at the surface of spilled oil because they are controlled by diffusion. If these products are leached from the surface of the oil and enter the water column, they are rapidly diluted to low concentrations. Therefore, they are not likely to have significant ecological impact.
- High-energy rocky shores usually do not accumulate oil, and if impacted are subjected to rapid cleaning by wave action.

- Oil does not penetrate easily into fine sediments in the intertidal zone, but can sink into shingle, gravel, and coarse sand. In some cases oil may penetrate to the water table, which forms a natural barrier to further penetration.
- On sheltered shores with high biological productivity, oil can penetrate down biological pathways, *e.g.*, worm burrows and plant root systems. Oil may persist for many years in the sediments, especially if oxygenating biological activity (*e.g.*, new burrow formation) is depressed.
- Large accumulations of oil or mousse may incorporate beach material and harden to form asphalt pavements; these are gradually eroded but may persist for many years on the upper shore and on sheltered beaches.
- Physical 'removal' of oil by natural processes alone does not eliminate oil from the environment; it redistributes it. This redistribution can be beneficial—*e.g.*, when wave action cleans the shoreline, it facilitates dispersion of the oil in the water column, and increases the surface area of the oil droplets, thereby encouraging other degradation processes. However, such redistribution may also involve sediment-bound oil being transported to the seabed.
- The toxicity of hydrocarbons on the seabed can vary widely, depending on the composition of the oil, the organism exposed to it, the transport pathways, and the extent to which the hydrocarbons can be degraded in the bottom sediments.

NATURAL RECOVERY

- Diving seabirds suffer heavy mortalities from oil. However, the mortalities arising from a single oil spill are not significantly different from natural mass mortalities experienced from time to time and are significantly less than annual mortalities from fishing activities.
- There is no evidence that seabird populations are declining as a result of oil spills. In fact, North Atlantic populations of most species have been increasing in recent years despite heavy annual losses from oil pollution.
- Kills of adult fish from exposure to oil are rare. The only important casualties from oil spills are rockfish and shellfish in near-shore waters, and fish in mariculture installations.
- Loss of pelagic eggs and fish larvae, when these are present at the time of an oil spill, has had no detectable impact on the fish stocks available to the fishing industry.
- Annual recruitment of fish stocks fluctuates naturally, and the size of the catchable stocks is determined more by the activities of the fishing industry (*e.g.*, over-fishing) and by climatic changes than by any other factor.

- Although the toxic components of petroleum hydrocarbons kill planktonic organisms, there is no evidence that these effects have any ecological significance in open waters. In closed waters, effects may persist for several months.
- To date, there are insufficient data in the scientific literature on marine mammal mortality and recovery to assess impact on breeding populations.
- Estimates of recovery times vary depending upon the environment. Past experience has shown that exposed, rocky shores usually recover in 2 to 3 years. Other shorelines show substantial recovery in 1 to 5 years with the exception of sheltered, highly productive shores (*e.g.*, salt marshes), which may take 10 years or more to recover.
- Subtidal sand and mud systems recover in recognisable successions. Usually, recovery times are 1 to 5 years, but they can be 10 years or longer in exceptional cases.
- Biological recovery of low-energy soft-substrate (sand, mud, *etc.*) ecosystems follows a generally well-defined course; but there are several alternative recovery routes for hard-substrate (rock, boulder, *etc.*) ecosystems, and the restored community may not be the same as that before the damage.
- Sublethal effects have been shown to occur after an oil spill and have been considered in the estimate of recovery times stated here. There is no evidence that sublethal effects are of any longer-term ecological significance.
- The early colonisers, once the physical and toxic effects of the oil ameliorate, play an active role in the breakdown of the remaining hydrocarbons.
- Removal of oil using drastic cleaning methods, beyond initial bulk oil removal, can actually delay recovery because the cleanup also removes living organisms and damages the habitat.

SCOPE AND OBJECTIVES

The objectives of this paper are, in the context of an oil spill, to provide:

- Practical working definitions of the terms 'clean' and 'recovery'
- A framework for understanding natural cleaning and recovery processes and their duration in cold water environments

The review draws only on published scientific information relating to oil spill incidents and relevant field trials and excludes the tropical environment.

This paper has been organised so that concepts, definitions, and other background information are presented in the earlier sections. The reader who wishes to skip this tutorial information should turn to the section entitled 'Natural Recovery,' which addresses recovery of biological systems (birds, fish, etc.).

An italicized summary statement is given at the beginning of major sections in the paper. The primary message of the paper can be obtained by reading only the italicized statements. A Glossary that gives definitions of selected technical words or phrases used in this report is also provided.

BASIC CONCEPTS

WHAT IS MEANT BY CLEAN?

Clean, in the context of an oil spill, is defined here as the return to a level of petroleum hydrocarbons that has no significant detectable impact on the function of an ecosystem. The size of the ecosystem is obviously an important consideration. It is not microscopic, but is large enough to include the major plant and animal communities. Practical application of this definition requires taking into account the relative proportions of oiled- and uniled-habitats. This definition does not necessarily require a return to some pre-existing background level, or the complete removal of hydrocarbons from the environment.

Authors such as Myers and Gunnerson (1976) have concluded that both biogenic and petrogenic hydrocarbons are ubiquitous. Thus it is unrealistic to define clean as a complete absence of hydrocarbons or a complete absence of petrogenic hydrocarbons.

Examples of published information are given in Table 1 (water samples), Table 2 (sediment samples) and Table 3 (mussel samples). The first general observation that may be drawn from these examples is that all samples contain hydrocarbons.

It can be seen from Tables 1 to 3 that background levels vary considerably. General observations from the tables are:

- Higher background levels in water, sediment, and biota are found in nearshore waters, particularly in urban and industrialized bays and inlets, because of the proximity to land-based discharges and combustion products and the greater frequency of shipping.
- Hydrocarbons may accumulate in sediments or biota to higher background concentrations than are found in water.

In the absence of a spill, these may be called background hydrocarbons. Possible sources are

- Organisms, *e.g.*, leaf waxes and hydrocarbons synthesised by algae
- Natural seeps of petroleum hydrocarbons, such as occur, for example, at Scott Inlet and elsewhere along the northeast coast of Baffin Island (Levy, 1981), and in the Santa Barbara Channel (Spies and Davis, 1979)
- Airborne combustion products, either natural (*e.g.*, from forest fires) or man-made (*e.g.*, from the burning of fossil fuels)
- Normal operational discharges (*e.g.*, bilge water) from ships and boats, including tankers, cargo ships, fishing and cruise vessels, and private boats
- Normal land-based discharges, *e.g.*, rainwater run-off from roads and urban areas, sewage discharges

It is possible to distinguish petrogenic from biogenic hydrocarbons only by using highly specific and sensitive analytical methods, notably capillary gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). Petrogenic hydrocarbons can be distinguished, for example, by their n-alkane distribution, pristane/phytane ratio, and the area of the unresolved complex mixture (UCM) 'hump' on the GC traces. Polynuclear aromatic hydrocarbons (PNAH or PAH) occur in crude oil but are also a significant constituent of combustion products (both natural and man-made).

Further information on this subject is available in the literature, *e.g.*, Broman *et al.* (1987), Foster and Wright (1988), Johnston *et al.* (1985), Knap *et al.* (1982), Law and Fileman (1985), Little *et al.* (1987), Mattsson and Lehtinen (1985), Mix and Schaffer (1983a, b).

The capacity of organisms such as bivalves to accumulate hydrocarbons (and other compounds) has led to their use as 'indicator' organisms to reflect spatial and temporal patterns in the compound of interest. As suggested by Table 3, mussels have been particularly widely used for this purpose. 'Musselwatch' sampling design and data interpretation have to take into account possible sources of variation; for example, the season (stage of reproductive cycle) or site (*e.g.*, tidal depth).

The interpretation of hydrocarbon data from sediments should consider the sediment properties, notably grain size and indigenous organic matter, which influence hydrocarbon adsorption and retention (Law and Fileman, 1985; Little *et al.*, 1987). The interpretation of

hydrocarbon analytical data in general has to take into account the fact that different analytical methods (e.g., infrared, ultraviolet fluorescence, GC) measure different things, so results from different methods are not directly comparable. Even if the same method is used, analytical variability also has to be taken into account (Farrington *et al.*, 1988; Howells *et al.*, 1989; Law *et al.*, 1987). Farrington *et al.* (1988), considering the results of a 22-laboratory intercomparison exercise, conclude that there is a need for much improvement for within- and between-laboratory precision.

WHAT IS MEANT BY RECOVERY?

Oil spill damage takes various forms: commercial, recreational, ecological, or aesthetic (though these may be interrelated). Recovery processes take many forms, which act on different time scales.

Recovery of the Use of Resources

The sea and coastlines are used in various ways for commercial and recreational purposes (human services) by the human population. Human uses of a spill-impacted area generally resume as soon as bulk oil is removed. In many cases, the availability of human services is not closely related to biological recovery and is usually more rapid than biological recovery.

Nature of Resources. Human uses of the resources of the coastal regions of cold water marine ecosystems include fisheries (commercial and sport finfish; shellfish), tourism, nature viewing (including bird-watching), hunting, camping, boating/kayaking and, under rare circumstances, sunbathing/beach use.

The availability of a resource (except for shell fisheries) is usually restored as soon as bulk oil is removed from the water surface and from the most heavily impacted region, which is the intertidal zone. Failure of the actual use of a resource to recover as quickly as the resource becomes available is usually a consequence of public perceptions.

Fisheries. Commercial and sport fishermen are generally excluded from fishing grounds where oil is floating on the water because of the risk of fouling fishing gear. Often it is possible to fish in areas unaffected by oil, and commercial fishing can continue with very little interruption even after a major oil spill. This was the case for larger fishing vessels in Brittany, France, following the wreck of the *Amoco Cadiz* (Fairhall and Jordan, 1980).

Fish stocks are rarely directly affected by oil spills, and a fishery in an area that has been exposed to oil can be reopened as soon as the area is free of floating oil. Recovery usually takes place in a matter of days or weeks and is independent of the biological recovery of damaged ecosystems.

On the other hand, when the fishery resource itself is damaged (e.g., clam beds, lobster fishery, mariculture installations), commercial damage will persist until exploitable stocks are restored. That may require deliberate restocking and a delay of 2 to 10 years, depending upon the age at which new stocks reach a commercial size.

Tourism. Many forms of tourism are unrelated to biological conditions, and therefore should be unaffected by oil spills, as long as the coastline and the water are clean. Minor oil contamination of bathing beaches by tarballs is regarded as a nuisance, and many coastal resorts regularly remove tarballs along with other beach litter in order to preserve local amenities. A detailed study made in the U.K. (PAU, 1973) could find no evidence that oil pollution had a detrimental effect on tourism, even at popular resorts in southwest England that had suffered from oil spills. This was not the case in Brittany following the *Amoco Cadiz* oil spill in 1978, where the tourist season that year was commercially the poorest on record; even coastal sites far away from those impacted by oil were affected (Fairhall and Jordan, 1980). Holidays on the south Brittany coast, far from the spill, were cancelled, with oil being given as the excuse. Recovery to pre-spill tourism levels occurred the following summer.

Tourist activities which are related to the biological environment, e.g., bird-watching, resume as soon as bulk oil is removed from an impacted area.

Seaweed Harvesting. In some areas seaweeds and kelp are harvested for the manufacture of alginates used in shampoos, cosmetics, and bath liquids, food additives, and for processing into animal feeds. Since oil does not adhere to the slimy surface of seaweeds and kelp, these plants are little affected by an oil spill. The factory processes used in the manufacture of products from kelp eliminate gross hydrocarbons, so even residual contamination of the crop does not affect its commercial value. This is not true of seaweeds harvested from the shore. The start of the seaweed harvest on the Brittany coast had to be delayed one month until the oil had cleared sufficiently, following the wreck of the *Amoco Cadiz* on the French coast in 1978. The kelp harvest was normal, but the harvest of intertidal seaweeds was seriously affected, largely because these seaweeds had been removed in large quantities by clean-up teams, but also because of the high levels of oil remaining in the areas that had been impacted (Fairhall and Jordan, 1980).

As mentioned above, human services in a spill-impacted area are generally available as soon as bulk oil is removed from both the water surface and the shoreline. However, biological recovery involves processes that begin in the presence of oil and continue to operate well after bulk oil is removed. Consequently, recovery of the availability of human services is achieved, in most cases, before biological recovery is realized.

Biological Recovery Processes

Biological recovery of an ecosystem damaged by an oil spill begins as soon as the toxicity or other damaging properties of the oil have declined to a level that is tolerable to the most robust colonising organisms. Subsequent events follow a well-established course which differs with the nature of the ecosystem, and the early colonisers assist in the removal of the oil.

Soft Substrata. In soft substrata (mud, sand) the following sequence of events follows damage caused by the input of any organic material such as sewage sludge, wood pulp waste (Pearson and Rosenberg, 1978), natural algal decomposition (Spies *et al.*, 1988) or oil (Kingston, 1987).

The initial phase of recovery is characterised by a small number of species, but in enormous numbers. For example, 'opportunistic' species of polychaete worms breed all the year round and young stages are always available to recolonise; they can tolerate adverse conditions that exclude most other animals and they feed on organic material. In the absence of competition and with an abundant food supply, they multiply rapidly. As conditions in the area improve, other, less hardy species are able to establish themselves and, by competition, reduce the numbers of the first colonisers. This process proceeds as conditions continue to improve and more sensitive species are able to re-establish themselves. Eventually a diverse fauna, characteristic of the area, is restored.

Hard Substrata. On hard substrates (rock, boulder, *etc.*) the recovery process is less predictable because the initial colonisers are all seasonal breeders, and the first species to colonise a bare surface may inhibit colonisation by others. On hard surfaces, it is the interaction between plants and animals and competition for space, rather than the physical and chemical conditions, that determine the path taken by the recovery process.

Lewis (1982) has made a long study of this subject and gives an expert account. Bare rocks are first colonised by a film of diatoms and the young stages of seaweeds (algae). If other events do not supervene, these will develop into dense stands of kelp (subtidal) or seaweeds (intertidal) with a rich associated fauna of worms, crabs and other crustacea, winkles and sea snails, *etc.* However, these dense stands of algae cannot develop if herbivores colonise the area at an early stage. The most important herbivores are sea urchin and abalone (subtidal) and limpet (intertidal). They graze down the young seaweeds, but make little or no impact on established stands of algae. If, because of this grazing pressure, the rocks are kept free of algae, they are available for colonisation by other encrusting animals such as barnacles that live happily with the grazers. Mussels, if they become established first, exclude both seaweeds and limpets.

Thus, the assemblage of plants and animals that recolonise a denuded hard surface depends on the time of year when colonising forms are available, and the first to arrive may determine the subsequent course of events. Predators such as starfish or carnivorous sea snails (whelks, *etc.*), if in sufficient numbers, may eliminate the mussels or barnacles and result in further change. The various routes that may be taken in the recovery of damaged

biological communities on hard substrata are no different from the changes that occur in these environments from natural causes.

Natural Fluctuations

Marine ecosystems are not stable, as is commonly assumed, but are in a natural state of flux and show erratic fluctuations from purely natural causes. This has now been established for all sectors of the marine environment for which adequate long-time series of observations have been made.

Different species of North Atlantic plankton monitored between 1948 and 1969 show wide year-by-year abundance fluctuations (Figure 1, Glover *et al.*, 1972). Cod in the North Atlantic, as recorded in numbers of fish landed, show a similar volatility in abundance (Figure 2, Jones, 1982). Herring and sardine abundance in traditional Japanese and Scandinavian waters can be traced from historical records back to the start of the 15th century; they too show periods of abundance and dearth that can be related to climatic change (Figure 3, Jones, 1982). Even the subtidal benthos, normally regarded as a stable environment, shows short-term changes, presumably related to climatic fluctuations (Figure 4, Buchanan *et al.*, 1978).

Subtle changes occur in intertidal muddy substrates. In one closely studied mud flat in northeast England, one common species of polychaete worm failed to breed in two successive years, for unknown reasons, and was replaced by a different, but closely related species (Olive *et al.*, 1981).

Rocky shores show the effects of climate and the biological interactions described above (Figure 5, Lewis, 1972) and naturally undergo wide fluctuations in the extent of cover by seaweeds, barnacles, mussels, *etc.*, in each case with corresponding changes in the fauna associated with them.

Natural Change and Impact Assessment. Sometimes damage attributed to oil spills can be caused by other factors. Limpets are dominant herbivores on rocky shores. If they are scarce, a cover of seaweeds follows; if they are abundant, seaweeds cannot become established and the rocks are colonised by other encrusting fauna. Young limpets settle on the rocks in early fall but are susceptible to air frost during the next few weeks. In years when there are early air frosts, most of the limpets are killed and the population is so small that seaweeds may develop (Figure 6, Bowman and Lewis, 1977).

Limpets are also killed by high summer temperatures. In one case on the north coast of Scotland, an accidental release of diesel fuel impacted a rocky shore. Afterwards, most of the limpets were found to be dead and the shore became densely covered with seaweed. This might have been regarded as a classical case of oil spill damage; but in fact, the beach had been regularly monitored, and it was known that the limpets had been killed by an exceptionally hot summer. These changes were already in train and the oil spill was irrelevant (Bowman, 1978).

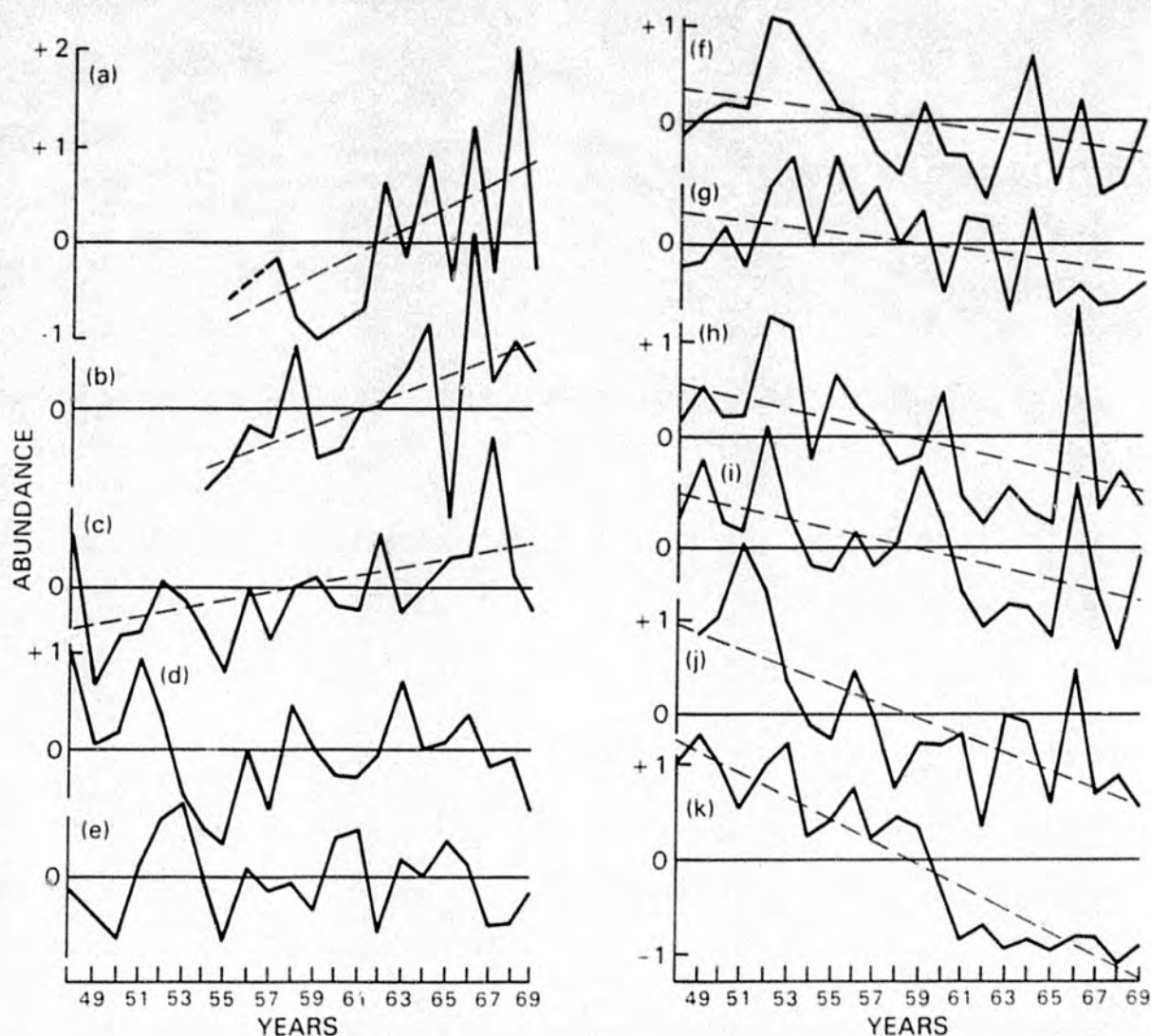


Figure 1: Changes in the abundance of zooplankton species in the North Atlantic. The organisms are: (a) *Pleuromamma borealis*; (b) *Euchaeta norvegica*; (c) *Acartia clausi*; (d) *Temora longicornis*; (e) *Clione lamacina*; (f) *Calanus helgolandicus* and *C. finmarchicus* stages V and VI; (g) *Metridia lucens*; (h) *Candacia armata*; (i) *Centropages typicus*; (j) *Spiratella retroversa*; (k) *Pseudocalanus* and *Paracalanus*. (After Glover et al., 1972.) The vertical axes give abundance variations expressed as standard deviations about a mean of zero. An annual abundance variation of one standard deviation less than the mean is -1. Standard deviations from the mean are calculated from annual abundance measurements for the 21-year period.

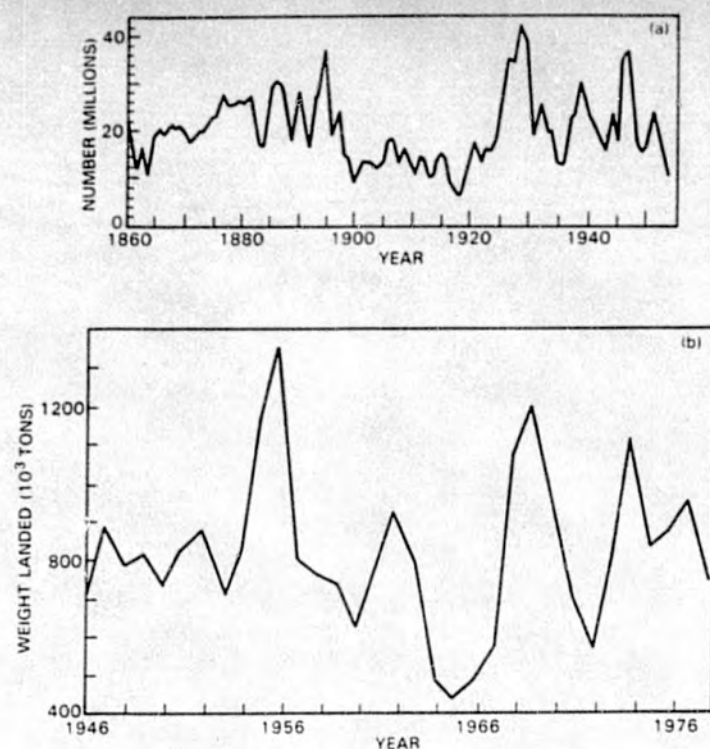


Figure 2: Landing of cod (a) in the Lofoten, Norway, fishery and (b) in the whole northeast Atlantic fishery (after Jones, 1982).

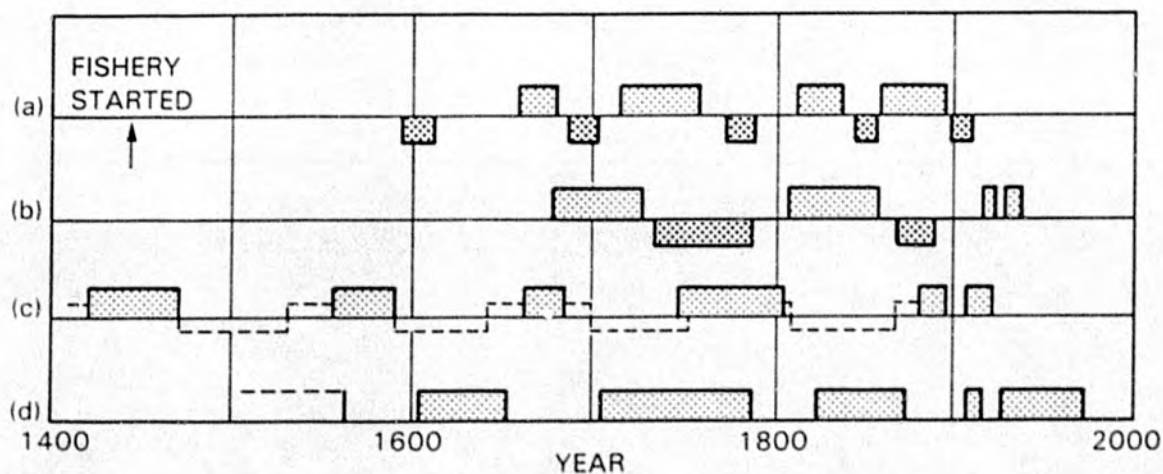
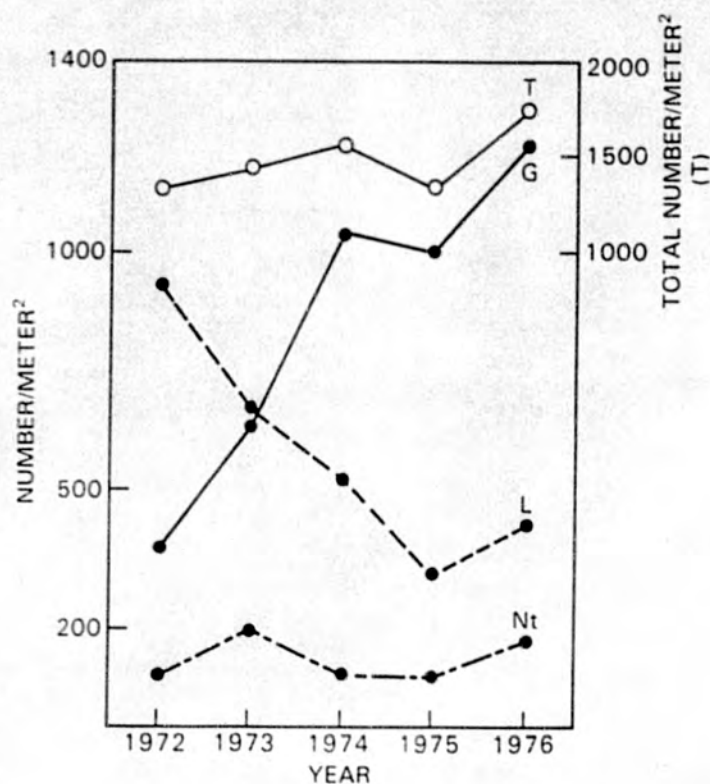


Figure 3: Periods of good and bad years (above and below line, respectively) for (a) Hokkaido herring; (b) Japanese sardine; (c) Bohuslan herring; (d) Atlantoscandian herring. (Dashed lines are speculative.) (After Jones, 1982.)



Gaining species 1972-6 (G)		Losing species 1972-6 (L)		Neutral species 1972-6 (Nt)	
Species	Gain/meter ²	Species	Loss/meter ²	Species	
<i>Paraonis gracilis</i>	238	<i>Spiophanes bombyx</i>	219	<i>Ampharete finmarchica</i>	
<i>Prionospio malmgreni</i>	144	<i>Chaetozone setosa</i>	129	<i>Glycera rouxi</i>	
<i>Myriochele oculata</i>	129	<i>Ampelisca tenuicornis</i>	112	<i>Goniada maculata</i>	
<i>Thyasira flexuosa</i>	115	<i>Amphiura filiformis</i>	50		
<i>Owenia fusiformis</i>	104	<i>Nephtys hombergi</i>	31		
<i>Magelona minuta</i>	100	<i>Scoloplos armiger</i>	26		
<i>Tharyx multibranchiis</i>	27	<i>Rhodine gracilior</i>	24		
		<i>Ammotrypane aulogaster</i>	17		

Figure 4: Contribution of the 17 most abundant species to the total number of individuals at one subtidal station off the northeast coast of England (after Buchanan *et al.*, 1978).

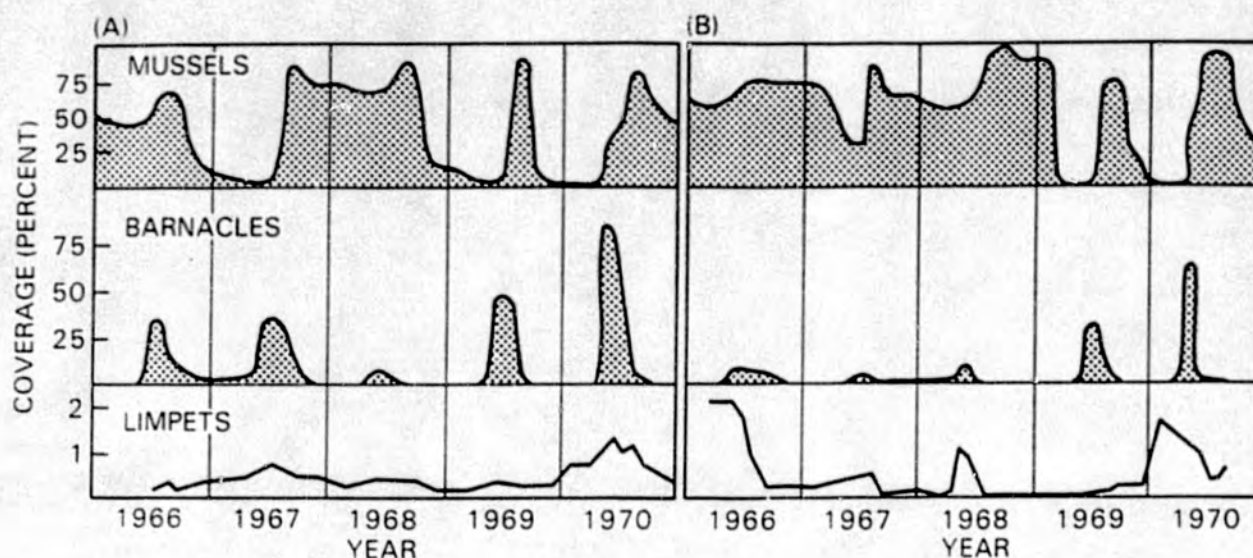


Figure 5: Fluctuations in the percentage cover on rocks by mussels, barnacles and limpets at two sites (A and B) on the north Yorkshire coast, 1966–1970 (after Lewis, 1972).

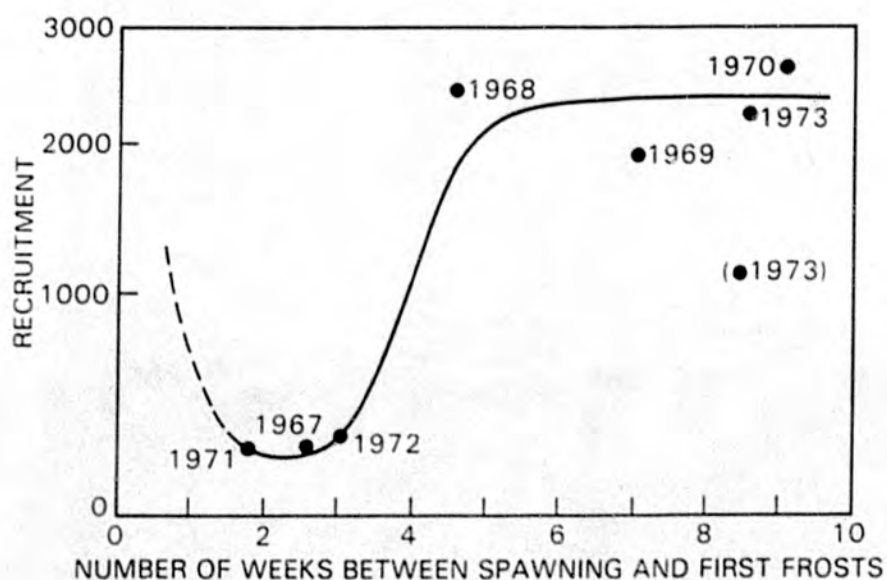


Figure 6: Relation between recruitment of limpets, *Patella vulgata*, and the duration of the frost-free period after spawning for the years 1967–1973. In 1973 there were two successional spawnings. (After Bowman and Lewis, 1977.)

In the same way, examination of two species of sea snails in Milford Haven in 1981 showed that there had been no substantial recruitment of young forms for 4 to 5 years (Figure 7). Milford Haven is the largest deep-water oil terminal in Europe, with five oil refineries around it; there are inevitable oil spills from tankers and these waters also receive waste water from refineries. It would be a natural assumption that the failure of recruitment of the sea snails while the oil terminal and refineries were in full operation was related to oil exposure. Not so. The two species are near the northern limit of their geographical range in Britain, and none of the fringe populations from south Wales to the north of Scotland had a successful recruitment during that time. The failure was due to climatic reasons, not oil (Lewis, 1982).

Given the above examples, it is clear that caution must be exercised in assessing the apparent damage as being due to oil spills.

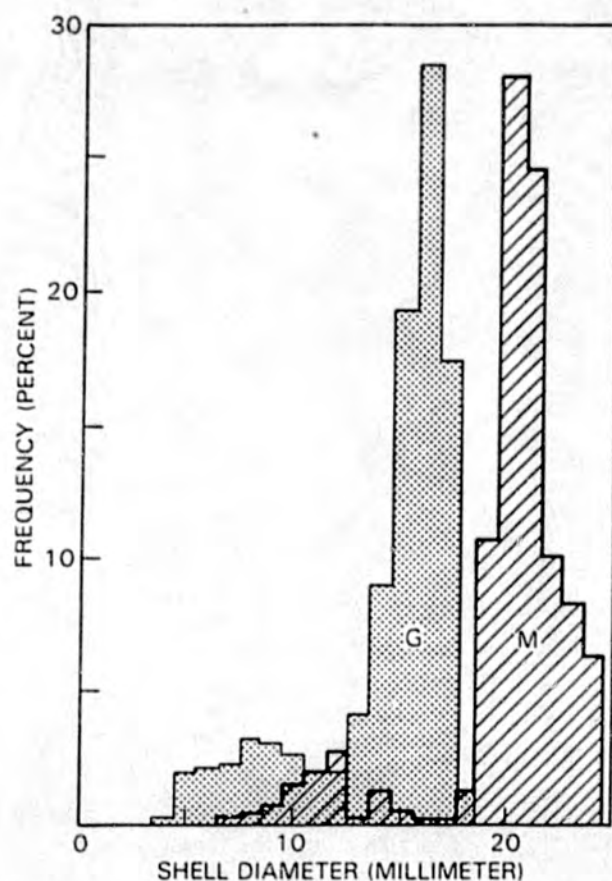


Figure 7: Size distribution of the intertidal gastropods *Gibbula* (G) and *Monodonta* (M) in a population on the Pembrokeshire coast, October 1981 (after Lewis, 1982).

A Working Definition of Ecological Recovery

Recovery is marked by the re-establishment of a healthy biological community in which the plants and animals characteristic of that community are present and functioning normally. It may not have the same composition or age structure as that which was present before the damage, and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have persisted in the absence of the spill.

Ecological recovery is a contentious subject on which there is room for legitimate disagreement (Southward, 1982; Clark, 1982). A synthesis of Clark's analysis (Clark, 1989) follows.

The state to which an environment returns after damage is often unpredictable. It depends upon the time of year, the availability of recolonising forms, biological interactions, climatic factors, *etc.* In any case, the ecosystem, had it not been damaged, would have changed in subtle or major ways during the period required for recovery.

The species of plants and animals generally available in the locality, which are the main components of a community appropriate to a particular habitat, re-establish themselves in northern waters within 2 to 3 years (RCEP, 1981). The members of the community then function and interact in a normal way, and for practical purposes the ecosystem has 'recovered'.

The restored communities will, of course, continue to show fluctuation and change, depending on climatic factors, biological interactions, the aging of some members of the community, or the establishment of rarer, but ecologically unimportant, plants or animals. Controversy arises over the view taken of these post-recovery changes.

Particularly in northern waters, many species are at the fringe of their geographical range. They exist in small, scattered populations and have a precarious existence. If one such population is eliminated by environmental damage, its nearest neighbours from which recruitment could take place may be many miles away. Recolonisation of a damaged area by these rare species will therefore depend on exceptionally favourable circumstances and may be protracted. It may not take place at all if climatic factors make these sub-optimal environments even less suitable.

It is unreasonable to demand that recovery depends on the re-establishment of the same age structure in the population as existed before the environmental damage. Lobsters, for example, can live about 20 years, although there are very few such grandfathers in any natural population and probably none in a lobster fishery. The existence of a few geriatrics in the population therefore is not a realistic criterion for recovery of a damaged ecosystem. In any case, few natural populations show an actuarial age structure; they are often dominated by a single year-class with little recruitment in the years before or after (see Figure 7, Lewis, 1982).

COLD WATER ECOSYSTEMS

Marine cold water ecosystems include those habitats found in temperate, boreal/antiboreal, subpolar, and polar seas (see Figure 8). One of the most significant differences between tropical and cold water habitats is the annual temperature variation. In tropical surface waters this difference is no more than 2°C, whereas in cold water ecosystems it may reach 10°C (Ekman, 1967). Temperature changes are seasonal in cold water ecosystems and are thus important in controlling cyclical biological events such as reproduction. As a result of thermally induced mixing of water layers, seasonal temperature changes are an important factor in enhanced productivity in these regions.

Animal and plant communities from cold water ecosystems tend to be less stable than those from lower latitudes, owing to the harsher environmental conditions. As a consequence, there can be considerable natural variability in community species composition from year to year. Animals from polar and subpolar regions tend to adopt reproductive strategies that involve either viviparous (live-bearing) or oviparous (direct development from egg to miniature adult) development. Since such strategies are associated with greater parental care, but fewer offspring per reproductive cycle, these animal populations are less likely to recover from major environmental damage as rapidly as those more southerly species producing vast numbers of planktotrophic (plankton-feeding) larvae.

The reader is referred to Appendix A for further details.

PHYSICAL AND CHEMICAL BEHAVIOUR OF SPILLED OIL

When oil is spilled at sea, a series of complex interactions of physical, chemical, and biological processes is immediately set in train (Koons, 1987). These processes are collectively called 'weathering' and are described in Appendix B. Evaporation of the volatile components is especially dominant in the initial phase following a spill. The evaporated components include most of the toxic constituents in crude oil, which, after evaporation, are rapidly diluted to background levels in the atmosphere. The persistence of oil slicks on the sea surface is dependent upon the type of oil spilled and sea state conditions. Some slicks can be removed by natural processes within a few days; other crude oils can form stable, highly viscous emulsions (mousses) and may persist for weeks or months in the open ocean. Eventually these slicks will form tarballs that are relatively harmless.

Oil concentrations in the water column below oil slicks are low. Because of the churning actions of waves in shallow waters, oil may become incorporated into sediments or more concentrated in the water column. Beached oil may be washed off and may also become incorporated into subtidal sediments. Alternatively, the oil on the beach may be refloated and transported to impact other stretches of the coastline, or dispersed into the water column as fine droplets. However, oil transported from beaches is usually weathered and less toxic than fresh oil. Oiled sediments on beaches can be buried under fresh deposits of sand. High-energy rocky shores usually do not accumulate oil and, if impacted, are rapidly cleaned by wave action.

The reader is referred to Appendix B for further details.

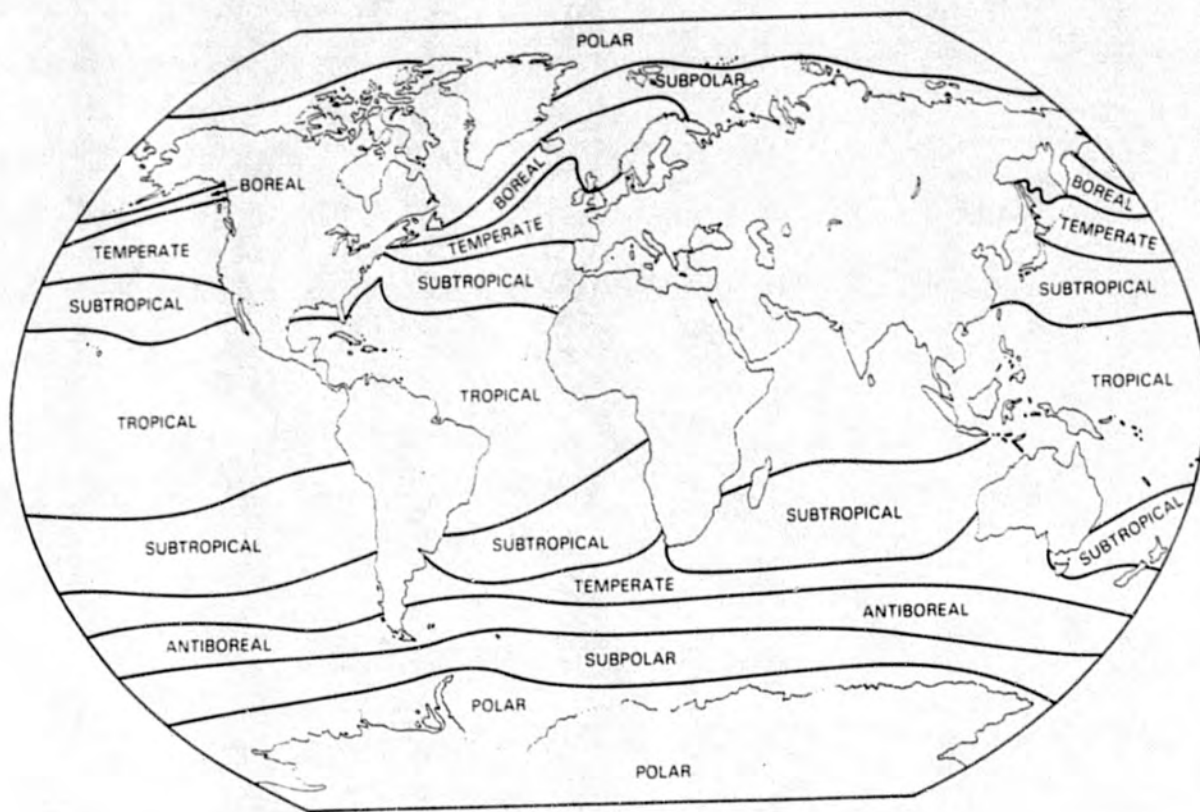


Figure 8: Map of the world showing the distribution of temperate to polar waters (Bogdanov, 1963).

NATURAL CLEANING

PHYSICAL REMOVAL BY NATURAL PROCESSES

The penetration of oil into shores, and the subsequent retention, redistribution, and escape of subsurface oil are influenced by shore physical characteristics, including exposure to wave action, sediment grain size, and position of the water table. Sediment transport pathways may move oil along shores or into subtidal areas, where grain size is again important in influencing oil retention.

Physical removal of oil from the shoreline by natural processes by itself does not eliminate oil from the environment; it redistributes it. Complete removal of oil from impacted shorelines, in terms of degradation of hydrocarbons to water and carbon dioxide, is effected partly through abiotic chemical reactions but mainly by biodegradation. Nevertheless, physical redistribution can be beneficial; for example, wave action may remove oil patches from a rocky shore and redistribute the oil in the form of relatively small drops in the water. This cleans the shore, and increases the surface area and aeration of the oil, thus facilitating biodegradation.

Physical removal from a particular area of a shore may also take place via sediment transport into an adjacent area ashore (McLaren, 1984) or into subtidal areas, where it is likely to continue to travel in the direction of sediment movement (McLaren and Little, 1987). The partitioning of oil into shoreline stranding, particle formation and transport, and sedimentation and biodegradation has been modelled by Gundlach *et al.* (1985) and Gundlach (1987). The estimation and quantification of oil on shorelines has been discussed by Owens (1984, 1987).

There is considerable information on physical removal/residence times of oil for different types of shore, resulting both from observations following spills and from experimental work. Such observations (a range of which are summarized in Table 4) form the basis for a number of discussions on factors determining the behaviour of oil on shores (*e.g.*, Owens, 1978, 1985; Tsouk *et al.*, 1985; Wolfe, 1987). In particular, they have been used to produce shore vulnerability or sensitivity indices which summarize the behaviour of oil on different types of shore and which can be used for predictive purposes and oil spill contingency planning. The best known index, used as the basis for many projects, is that of Gundlach and Hayes (1978), and this is reproduced in Table 5. An example of a regional application (the index applied to the Alaskan coast) is given by Gundlach and Hayes (1982). Vulnerability indices may be constructively used with removability indices which rate shore types in terms of how easily oil may be removed from them (Hann, 1988).

Factors affecting residence times include

- Overall exposure of the shore, from exposed rocky headlands to sheltered tidal flats and marshes (see Table 5). This in turn depends upon a number of variables that include fetch, speed, direction and frequency of winds, and open angle of the shore (Ballantine, 1961).
- Localized exposure/shelter—even on an exposed shore, cracks, crevices, and spaces under boulders can provide sheltered conditions where oil may persist.
- Steepness/shore profile—extensive, gently sloping shores dissipate wave energy.
- Substratum—oil does not penetrate easily into fine sediments, especially if they are waterlogged, but can penetrate into shingle, gravel and some sand beaches (see Hayes *et al.*, 1979, and Long *et al.*, 1981, in Table 4). In some cases oil may reach the water table, which forms a natural barrier to further penetration.
- Height of the stranded oil on the shore—oil spots taken into the supratidal zone by spray can persist for many years, where it weathers to produce tarry residues (see Mottershead, 1981 in Table 4). Conversely, oil on the mid- and lower-shore is more likely to be removed by water action. It is common to have stranded oil concentrated in the high tide area (see Keizer *et al.*, 1978, and Owens *et al.*, 1987a, b, in Table 4).
- Oil type—*e.g.*, viscosity will affect movement into and out of sediment shores.
- Volume of oil—*e.g.*, heavy loadings lead to greater retention times in sediments (see Harper *et al.*, 1985 in Table 4).

CHEMICAL AND BIOLOGICAL DEGRADATION

The main type of change that hydrocarbon molecules may undergo on entering the marine environment is oxidation. This occurs either through abiotic chemical reactions, or through enzyme-controlled reactions in a variety of organisms, notably microorganisms. The toxicity of oil can vary widely, depending on the nature of the source and the extent of degradation. Oil reaching the shore or the seabed may already have been partly degraded, and will continue degrading at rates dependent on local environmental conditions. The main process involved is oxidation by microorganisms.

Chemical Degradation

Abiotic chemical reactions are usually catalysed by light (photooxidation) and lead to the formation of a variety of oxygen-containing derivatives, including alcohols, ethers, dialkyl peroxides, and carbonyl compounds. Further details are given by Malins (1981), who also makes the points that the transformations of petroleum create a formidable challenge for the

analytical chemist and that relatively little is known about the toxicity of oxidation products to various forms of marine life.

Factors affecting chemical oxidation include light intensity and duration, aeration, and oil thickness. Burwood and Speers (1974) found that aeration increased the chemical oxidation of crude oil under both subdued and direct sunlight. Riley *et al.* (1980) tested the effects of different simulated environmental conditions on the weathering of Prudhoe Bay crude over 24 days, and found that a combination of sunlight and water sprayed upon the surface of the oil (to simulate rough conditions) produced the largest decreases of the volatile saturated compounds and most of the aromatic compounds.

The complete degradation of some hydrocarbons may involve a combination of photooxidation and biodegradation. Hinga *et al.* (1986) studied the degradation of a polynuclear aromatic hydrocarbon, 7,12-dimethylbenz(a) anthracene (DMBA), in a marine microcosm. They concluded that the initial transformations, which affected almost all of the DMBA within hours, were primarily the result of photodegradation, but at least some of the photooxidation products were then subject to biodegradation resulting in production of carbon dioxide.

Biological Degradation

Microbial Degradation. Degradation occurs through oxidation reactions, and microbial degradation is an important process involved in the eventual disappearance of oil from the marine environment (Karrick, 1977). Reviews of microbial degradation of hydrocarbons are included in CONCAWE (1979), Jordan and Payne (1980), and Atlas (1985). Over 200 species of microorganisms are capable of degrading hydrocarbon compounds, and the species concerned are widely distributed bacteria and fungi, including those found in polar environments. Representatives of bacterial genera such as *Pseudomonas*, *Mycobacterium*, and *Nocardia* are capable of degrading both aliphatic and aromatic hydrocarbons (CONCAWE, 1979), as are some fungi such as *Cladosporium resinae* (Walker *et al.*, 1973). Other species are more restricted in their hydrocarbon utilisation. Details of species, hydrocarbons utilised, and metabolic pathways are given by Jordan and Payne (1980). CONCAWE (1979) identifies *Desulfovibrio desulfuricans* as an anaerobic hydrocarbon-degrading bacterium, though its degradation power is very slight (Wallhauser, 1967).

A number of observations on microbial degradation are summarised in Table 6. As exemplified in the Stewart and Marks (1978) study, hydrocarbon-utilising microorganisms multiply rapidly following an input of oil and subsequently decline as the oil is degraded. Degradation rates vary considerably, and a number of rate-limiting factors can be identified. Experimental work (*e.g.*, Colwell *et al.*, 1978, and the Baffin Island experiments summarised by Atlas, 1985) shows that nitrogen and phosphorus nutrients can be limiting. Biodegradation can be stimulated by the right kind of fertiliser application, even in polar and subpolar conditions.

Because degradation is oxidative, it proceeds slowly in low oxygen concentrations. These may come about in various ways. For example,

- Reduced accessibility because of relatively large amounts/thicknesses of oil (Colwell *et al.*, 1978; Fusey and Oudot, 1984)
- Consumption of oxygen by normal organic decay processes such as occur in piles of rotting seaweed (Sveum and Sendstad, 1985)
- Reduced penetration of oxygen into deeper sediments (Mille *et al.*, 1984)
- Limited circulation of interstitial water in fine-grained sediments

It follows that natural processes that can increase aeration, such as the worm activity described by Gordon *et al.* (1978), or some types of natural physical redistribution as described in the section on physical removal, can increase microbial degradation.

Colwell *et al.* (1978) concluded that temperature was not a limiting factor for degradation of hydrocarbons in the Straits of Magellan; however, there is some evidence that it can be elsewhere. Arhelger *et al.* (1977) found that dodecane oxidation rates were 0.7 g/litre/day in Port Valdez, 0.5 g/litre/day in the Chukchi Sea, and 0.001 g/litre/day in the Arctic Ocean. This difference with latitude is consistent with the experimental results of Haines and Atlas (1982), who found evidence of biodegradation only after one year in the case of Prudhoe Bay crude in Beaufort Sea sediments. Temperature limitation may operate seasonally. For example, the average degradation rate for n-hexadecane in experiments on Baffin Island (Atlas, 1985) varied from 9.5 to 43.8 $\mu\text{g}/\text{m}^3/\text{day}$ for water, with the highest rates occurring in early August.

Petrogenic hydrocarbons can accumulate in subtidal sediments in various ways. Microbial activity may be present, but unable to cope with a high rate of continuous hydrocarbon input (*e.g.*, an area of the North Sea described by Massie *et al.*, 1985b). This example is relevant to possible post-spill scenarios, *e.g.*, continued leaching of relatively fresh oil from thick upper shore deposits to areas further down the shore.

The sediment may be oxygen- and/or nutrient-limited for various reasons, or if the route of the hydrocarbons to the seabed has been long and aerobic, the residues entering the sediments may be mainly complex high molecular weight compounds, which are relatively resistant to biodegradation. For example, in Milford Haven bottom sediments the bulk of the hydrocarbons is from degraded petrogenic sources, possibly representing the degradation residues of a wide variety of oil types (Little *et al.*, 1987).

Other Pathways. Many marine organisms including fish, crustaceans, and molluscs have been shown to have the capacity to convert hydrocarbons to metabolites; aromatic compounds have been studied in particular. The conversion of aromatic compounds to oxygenated derivatives takes place via enzyme (mixed-function oxygenase) systems. Malins (1981) gives examples of metabolic pathways and their products, which include glucuronides, glycosides and mercapturic acid derivatives.

Several studies reviewed by Malins (1981) have indicated that hydrocarbons are readily depurated from body tissues if organisms are placed in 'clean' environments; see also Page

et al. (1987). However, the hydrocarbon metabolites tend to increase or remain constant in organisms for long periods. These may affect the organisms concerned; for example, mussels from the *Amoco Cadiz*-oiled sites had increases in polar aromatic compounds, and this was associated with observed cellular damage, *e.g.*, increases in lipid and lysosomal granules (Malins, 1981).

The metabolic activities of marine organisms can transform hydrocarbons (so removing some of them from the environment). Relatively little is known about the environmental significance of the oxidation products, some of which are also toxic compounds. However, because of the rapid dilution of the compounds in the water column compared with their slow rate of production, they are unlikely to have significant ecological impacts.

NATURAL RECOVERY

BIRDS

Seabirds are among the most conspicuous casualties of oil slicks and, as such, attract considerable public attention. But there is no reason to suppose that, from a biological point of view, this mortality is damaging to seabird populations. Arctic and sub-Arctic seabirds also suffer heavy mortality from natural causes and from fishery practices. Even the auks, which because of their very low reproductive rate might be expected not to be able to make good these losses, have sustained their population; and there is no evidence that other seabirds with a greater reproductive potential have declined in numbers.

Losses of Seabirds from Oil

Estimates of the number of casualties of seabirds from oil slicks are highly speculative. The only firm figures are counts of the number of oiled birds coming ashore, but these are subject to severe limitations depending on the intensity of the search, accessibility of the shoreline to observers, *etc.*, and some carcasses may have become oiled after death from natural causes. An unknown number of oiled birds may die at sea and not reach the coast. Tests by the RSPB (1979), when marked seabird corpses were released at sea, gave variable recovery rates on the shore, depending on the distance and direction of the coast, wind speed and direction, and accessibility of the shoreline to observers. Sea conditions are also likely to have a radical influence on the number of birds coming ashore.

There is little relation between the size of an oil spill and the number of seabird casualties. At least 12,000 birds of various species were killed when one or more oil slicks (which were never positively identified despite aerial surveillance, and on that account were probably small) moved up the coast of northeast England and east Scotland in January and February 1970 (Greenwood *et al.*, 1971).

One of the largest kills of seabirds by oil on record was in the Skagerrak (strait between Denmark and Norway) in January 1981, when some 30,000 oiled birds appeared on neighbouring beaches (Mead and Baillie, 1981). This was caused by a relatively small amount of oil released by perhaps two ships (RCEP, 1981). On the other hand, the greatest volume of oil released in any shipping accident, following the wreck of *Amoco Cadiz* on the Brittany coast in March 1978, when 230,000 tons of crude oil and bunker fuel were released over a period of 3 to 4 weeks, caused the known death of only 4,572 birds (Hope-Jones *et al.*, 1978), though the actual total was undoubtedly higher.

The greatest concern must be about the repeated losses of seabirds from oil pollution in areas where oil slicks occur frequently and pollution verges on chronic. The English Channel and North Sea are among the most heavily trafficked sea lanes in the world, and casual oil discharge from shipping has been a regular feature since the 1920's. The surrounding coasts are populated with bird-lovers, and monitoring of the numbers of oiled birds coming ashore has been unusually complete (Bourne, 1976).

Experience of the incidence and consequences of oil pollution in the northeast Atlantic offers the best available factual base for an assessment of the impact of oil on seabirds. The claim of Morzer-Bruyns and Tanis (1968) that 150,000 to 450,000 seabirds are killed annually by oil in the North Sea and North Atlantic has a slender factual base and may be an order of magnitude too high (Dunnet, 1982; Clark, 1987); but this chronic and small-scale oil pollution may be responsible for at least as many seabird deaths as those resulting from spectacular accidents (Croxall, 1977). However, if the annual mortality from oil is of the order of tens of thousands of seabirds a year, this must be set against a calculated annual mortality from natural causes of well over one million (Dunnet, 1982).

Other Causes of Mass Seabird Mortality

Many seabirds suffer mass mortality from causes other than oil. Harsh weather in winter and prolonged storms prevent their feeding and they become severely emaciated; if they do not starve, they are at risk from any additional stress. 'Wrecks' (mass mortality) of seabirds are erratic but frequent and may result in losses comparable to those following major oiling incidents. In autumn 1969, some 12,000 seabirds, mainly murre, died in the Irish Sea and western Scotland. Some were slightly oiled, some contained high levels of PCB's in their body fat, but all were severely emaciated and the most significant cause of death appears to have been prolonged storms (NERC, 1971). The wreck of the *Amoco Cadiz* appears to have coincided with a 'wreck' of puffins on the Brittany coast from natural causes, which augmented the casualties (Hope-Jones *et al.*, 1978). Even larger 'wrecks' of guillemot (100,000+ birds) have been reported from Alaska (Bailey and Davenport, 1972).

Failure of the food supply is a natural hazard of seabirds at high latitudes. Croxall and Prince (1980) reported that the absence of swarms of krill around South Georgia in 1977 to 1978 (krill are shrimp that are a major food source for many animals in the Antarctic) resulted in the failure of krill-eating birds, mainly gentoo penguin and black-browed albatross, to rear their chicks. The reproductive failure of puffins on the island of Rost in

the Lofoten Islands in most years of the 1970s appears to have been due to a shortage of young herring, sand eel, and sprats, which are the principal food of the young (Mills, 1981).

The use of mono-filament gill nets is responsible for heavy seabird losses. These nets may be 30 or more kilometres long and trap not only fish, but also diving seabirds and sea mammals (seals, dolphins, *etc.*), which then drown. Nets that break free may drift at sea for a very long time (they are virtually indestructible) and 'fish' passively throughout that period. It has been estimated that the Danish salmon drift-net fishery in the North Atlantic killed 250,000 to 750,000 seabirds, mostly Brunnich's guillemot, each year between 1965 and 1975 when the fishery was exploited. The Japanese salmon fishery in the North Pacific and Bering Sea is estimated to have taken a toll of between 214,500 and 715,000 seabirds per year between 1952 and 1975, and between 350,000 and 450,000 per year during the 1975 to 1978 period (Clark, 1989). These figures are of the same order of magnitude as the most pessimistic estimate of the annual mortality of seabirds from oil in the northwest Atlantic and are quite possibly ten times greater.

Population Effects

While the death of oiled seabirds attracts a great deal of public concern, from a purely biological point of view what matters is not these deaths but the number and fate of the survivors. Most animals overproduce young, often on a colossal scale, and nearly all of them die before reaching the age of reproduction. Additional deaths from exposure to oil may be insignificant in comparison with the mortality from natural causes. Animals with a large breeding potential may rapidly make good such losses. Mortality is only significant if it results in a substantial decrease in the population, particularly in the breeding population (McIntyre *et al.*, 1978).

Auks present the worst-case scenario. They spend nearly all their time on the surface of the sea in dense flocks. Not only are they particularly at risk from floating oil, but casualties are likely to be large. More importantly, their breeding biology does not suggest that they would be able to replace losses from oil rapidly. Murres do not breed until they are 3 to 7 years old and then do not breed every year. They nest on precarious cliff ledges and lay only one egg. The eggs or chicks often fall off the ledges or are taken by predators. In one Scottish colony, common guillemots had only a 20 percent chance of successfully rearing a chick (Southern *et al.*, 1965), and a similar low success rate has been found in colonies of Brunnich's guillemot in Canada (Tuck, 1961). If the egg or chick is lost, the birds abandon breeding for that year. Once a chick successfully reaches the sea, it has few predators and has an average annual survival rate of over 90 percent (Dunnet, 1982). Thus the larger auks and a number of other seabirds have a life expectancy of 20 years or more.

A decline in the southerly populations of several species of auks that suffer heavy casualties from oil, including murres and razorbills (Tuck, 1961; Clark, 1978) and puffins (Bourne, 1971; Kress, 1977), has taken place on both sides of the Atlantic. This apparently confirmed the prediction that birds with such a low replacement rate could not sustain repeated losses from oil and that this population decline was the result. However, detailed

censuses have shown that while colonies at the southern fringe of their geographical range have been declining, others (some equally exposed to oil) are either stable or have shown a dramatic increase in recent years (Harris and Murray, 1981; NERC, 1977). These population changes are thought to be due to the amelioration of climate in the North Atlantic during this century and the northward shift of the main centres of population of sub-Arctic species (Clark, 1984). Oil has not been a factor.

The growth of some colonies has been so rapid as to confound previous predictions, and how it has come about is still uncertain (Dunnet, 1982). Leslie (1966) calculated, from what was known about replacement and survival rates, that it would take a colony of guillemots 53 years to double in size. In other words, if half the colony were killed by an oil spill, restoration of the numbers would take half a century by natural growth. More sophisticated simulations specifically related to guillemot populations in the Bering Sea and Gulf of Alaska yielded comparable predictions of recovery time of 20 to 40 years, depending on the size and location of an oil spill (Ford *et al.*, 1982), and 70 years (Samuels and Lanfear, 1982). Clearly, the increase in northern populations of auks has been so widespread that the numbers in a depleted colony cannot have been made good simply by immigration from other colonies and at their expense. One explanation may be that young birds are entering the breeding population at an earlier age than previously (Dunnet, 1982). The large population of young, non-breeding adults therefore provides a reservoir from which depleted breeding colonies can be replenished if necessary.

Sea ducks, the other major casualties from oil, have much greater recovery potential. They start to breed at a younger age, lay much larger clutches of eggs, and replace lost eggs (Dunnet, 1982).

Only diving sea ducks suffer casualties from floating oil on a scale similar to that of the auks, but they have a much higher reproduction rate and seem well able to withstand this mortality without affecting the population size. Reports of a decline in the numbers of old squaw (long-tailed duck) and velvet scoter migrating through the Baltic (Bergmann, 1961; Lemmetyinen, 1966), which was attributed to the consequences of exposure to oil in the North Sea winter quarters, were based on estimates, not reliable censuses. Whatever the value of these observations, such a claim has not been made since then.

An example of the recovery potential of sea ducks is given by the experience of an oil spill in Finnish waters in the northern Baltic that affected a colony of eider duck. These birds have a relatively small clutch size compared with other sea ducks and tend to remain attached to a particular site. Following the grounding of the tanker *Palva* in 1969, 25 to 33 percent (2400 to 3000 birds) of the local eider colony were killed, but in the following year, the number of breeding birds was fully restored; indeed, the eider population is said to have been exceptionally large (Leppakoski, 1973).

Cleaning and Rehabilitation

Cleaning and rehabilitation of oiled seabirds are possible if adequate facilities are available. These efforts may be carried out on humanitarian grounds but have no ecological value (Clark, 1973; NRC, 1985).

Polar Conditions

Almost all the reliable scientific information about the impact of oil on seabirds is, understandably, from the northeast Atlantic and the North American coast south of Newfoundland. At higher latitudes, colonies of auks are an order of magnitude larger in size than colonies farther south, and flocks on the water are correspondingly greater. Although there is no evidence, it must be expected that casualties in an oil spill incident would be greater in higher latitudes than those in northeast Atlantic waters. However, Arctic populations have not suffered from recurrent exposure to oil for the last 70 years in the same way. Arctic populations of auks are said to be already in decline (NRC, 1985), but in the absence of censuses (impracticable under the circumstances), this claim, although it may be true, is without firm foundation.

The reader is referred to Appendix C for details concerning effects of oil on birds.

FISHERIES

There is a general consensus among fishery authorities that oil spills are damaging to fin-fisheries by excluding fishermen from fishing grounds for the period while oil is on the water, by the fouling of fishing gear, but most importantly by the public's fear of tainting of the fish which can have a serious effect on the market. Mobile fish species appear to be able to avoid oiled areas, and fish kills among them have not been recorded. Non-mobile, inshore rockfish may be killed, and, of course, fish in mariculture enclosures cannot escape and are likely to be killed if exposed to oil.

There can be a heavy loss of pelagic eggs and fish larvae if these are present at the time of an oil spill, although this has rarely been observed directly. In most cases this mortality has had no detectable impact on the fish stocks available to the fishing industry. Annual recruitment to these stocks fluctuates naturally, and the size of the catchable stock is determined more by the activities of the fishing industry (e.g., overfishing) and by climatic changes than by any other factor.

Shellfish (e.g., clams, oysters) in inshore or intertidal sediments are very vulnerable to oil, and severe and protracted damage may be caused to them by an oil spill.

Interference

The immediate effect of an oil spill is the exclusion of fishermen from fishing grounds where there is a risk of encountering floating oil. Fishing gear cannot be shot, or if an oil slick drifts through an area where fishing is in progress, the fishing gear is likely to become fouled with oil. The catch is then valueless and the gear has to be replaced. Fishing vessels are likely to be fouled also, but they can be cleaned.

Gear fouling by oil is most damaging in the case of fixed installations, though it is possible to protect them by the deployment of booms, *etc.*

Tainting

The greatest commercial impact of any resulting from oil spills probably comes from the public's fear of tainting (see, for example, Fairhall and Jordan, 1980; Clark, 1989).

Tainting is the change in the characteristic flavour or smell and may be caused by petroleum hydrocarbons being taken up in the tissues or contaminating the surface of the catch. Light to middle boiling range oils are the most potent source of taint, but it can be caused by any oil (Whittle, 1978). The concentration of oil required to cause tainting varies widely with the oil and the fish concerned (McIntyre, 1982). Fatty fish, such as salmon or herring, develop taint more readily than non-fatty fish; but even salmon lose their taint after 4 weeks, despite continuous exposure to oil (Brandal *et al.*, 1976).

In some countries a particular hazard occurs when shellfish (shrimp, molluscs) are boiled in bulk before marketing. One or two specimens with adhering oil can then taint the whole batch.

Commercial shellfish and finfish markets are subject to irrational reactions in a way not experienced by other food markets. Even the suspicion that seafood may be tainted is sufficient to depress the market significantly. Fish sales on the Paris market fell by half during the period of the *Torrey Canyon* oil spill, regardless of the quality or origin of the fish (Korringa, 1968).

Crude oil and refined products contain polyaromatic hydrocarbons (PAH), some of which are carcinogenic to mammals. Molluscs, in particular, are efficient accumulators of PAH, though they rapidly lose them when transferred to clean water. Human exposure to PAH through the consumption of contaminated seafood is not regarded as a public health risk, partly because of the public rejection of tainted seafood, but also because the total exposure to PAH from this source is small compared with that from other foods (cabbage, spinach, smoked or grilled fish or meat) (King, 1977; RCEP, 1981). Cabbage, for example, can contain twice the concentration of benzo(a)pyrene (a carcinogenic PAH) as clams from relatively polluted waters (RCEP, 1981).

Sublethal Effects

Experimental studies have shown that various pathological conditions, including fin erosion, ulceration of the integument, liver damage, and lesions in the olfactory tissue, can be induced in fish exposed to oil. However, it is not clear that any of these conditions, when observed in fisheries, are related specifically to exposure to oil; they appear to be a response to pollution-induced stress in general.

Fin erosion affects the caudal (tail) fin of mid-water fish such as mullet, or the posterior fins most in contact with the seabed in bottom-living flatfish (Desaunay, 1981). Fin erosion is often accompanied by the development of abnormal bent fin rays. While a proportion of fish from any waters show these conditions, an abnormally high incidence of the condition has been reported in flatfish living on contaminated sediments in many parts of the world (Sindermann, 1982).

Following the wreck of the *Amoco Cadiz* on the Brittany coast, three species of flatfish (plaice *Pleuronectes platessa*, sole *Solea vulgaris*, and dab *Limanda limanda*) caught in two heavily oiled bays showed the following proportions with fin erosion: April 1978 (immediately after the oil spill), 0 percent; December 1978, 90 percent; May 1979, 73 percent; October 1979, 2.5 percent (Desaunay, 1981). It is not known if the decline in the proportion of affected fish was due to the recruitment of a new year-class, immigration from outside the affected area, recovery of the affected animals, or differential mortality of them.

Minchew and Yarbrough (1977) studied fin erosion in mullet kept in experimentally oiled brackish-water ponds. Caudal fin erosion was first noticed 12 days after the spill, and by 13 days all samples of exposed fish had fin erosion. Thirty-four days after the spill, some regeneration of fins was noted and this was still in progress on the 56th day.

Six months after the wreck of the *Amoco Cadiz*, 50 to 80 percent of a catch of mullet (*Mugil cephalus*) were found to have ulcerated bodies (Balouet and Baudin-Laurencin, 1980). There is no positive evidence to link this condition with the previous oil spill, but mullet maintained in experimentally oiled ponds (see above) developed integumental lesions (Minchew and Yarbrough, 1977).

Liver pathology has been demonstrated in English sole (*Parophrys vetulus*) after being maintained for 4 months on experimentally oiled sediments (McCain *et al.*, 1978), and a similar condition developed in Atlantic croaker (*Micropogon undulatus*) exposed to water-soluble fractions of crude oil (Eurell and Haensley, 1981). This condition, like fin erosion, is unlikely to be particularly related to exposure to oil, but is a general indicator of stress (McCain *et al.*, 1978). Liver lesions have been reported in killifish (*Fundulus heteroclitus*) sampled in an area that had been affected by an oil spill 8 years previously (Sabo and Stegeman, 1977), but there is no direct evidence to connect the pathological condition with the oil.

Pathological and degenerative changes in the olfactory membranes have been recorded in Atlantic silversides (*Menidia menidia*) (Gardner, 1975) and larval sand soles (*Psettichthys*

melanostichus) (Hawkes, 1980) experimentally exposed to water-soluble fractions of crude oils. These pathological conditions have not been reported in fish in the circumstances of oil spills, but no particular search has been made for them.

Eggs and larvae are more sensitive to the toxic effects of oil. Johannessen (1976) showed that the water-soluble extracts of Ekofisk crude reduce the hatching success of fertilized capelin eggs at concentrations of 10 to 25 ppb, and Tilseth *et al.* (1981), using the same oil, found reduction in growth and change in buoyancy of cod eggs and larvae after 14 days at 50 ppb. Larvae exposed to 250 ppb developed malformations of head and jaws that interfered with feeding.

There are numerous reports of petroleum-induced abnormalities in embryos and larvae of fish (Sindermann, 1982). These include malformed jaws, flexures of the vertebral column, reduced heart rate, loss of coordination and equilibrium, and degeneration of neurosensory cells. Following the *Argo Merchant* oil spill off Nantucket Island, eggs of cod and pollock showed cytological abnormality of the embryo's cells and arrest of cell division (Longwell, 1978).

Conan (1982) reported non-pathological sublethal effects in mullet and flatfish in the heavily oiled estuaries of the Brittany coast following the wreck of the *Amoco Cadiz*. Sediments in these low-energy embayments continued to release oil for two or three years following the spill, and during this period the fish showed reduced growth, fecundity, and recruitment.

Experience In Oil Spills

Following the wreck of the *Amoco Cadiz*, there was an immediate kill of several tons of rockfish at the site (CNEXO, 1981); but generally fish appear able to leave an oiled area, and kills of adults from the effects of oil are rare. Indeed, during the period when oil slicks were in the Santa Barbara Channel following the blowout in 1969, fish shoals were observed from the air by professional fish spotters in areas not covered by oil, and no heavy mortality of fish was recorded (Abbot and Straughan, 1969). After the *Tsesis* oil spill in the Baltic, and the wreck of the *Betelgeuse* in Bantry Bay, Ireland, herring (and also sprat in Bantry Bay) migrated through the oiled areas and spawned normally (Linden *et al.*, 1979; Grainger *et al.*, 1980).

The only important casualties from oil spills are of shellfish (crabs, clams) in shallow-water or intertidal sediments. The West Falmouth, Massachusetts, diesel spill in 1969 caused great initial mortality, and effects on crab populations were still obvious 7 years later (Burns and Teal, 1979). Populations of the clam *Mya arenaria* were still adversely affected 6 years after the grounding of the *Arrow* in Chedabucto Bay, Nova Scotia (Thomas, 1978).

Although recorded as 'sublethal', developmental abnormalities must be expected to lead to the early death of the young fish. Since they and damaged eggs sink to the bottom and rapidly decompose, it is difficult to estimate these losses in any oil spill. However,

Longwell (1978) reported that following the *Argo Merchant* oil spill, 20 percent of cod eggs and 46 percent of pollock eggs in the spill zone were dead or moribund. Smith (1970) reported that 90 percent of pilchard eggs were killed in waters exposed to oil from the *Torrey Canyon*, compared with a 50 percent mortality more distant from the oil; but the situation in that case is complicated by the extensive use of very toxic dispersants in that incident. On the other hand, after the explosion of the *Betelgeuse* in Bantry Bay, Ireland, oil leaked from the wreck for 18 months and dispersants were frequently used. During the spring, sprats and whiting spawned in the area, but no adverse effects on eggs or larvae were detected (Grainger *et al.*, 1980).

The loss of fish eggs and larvae from oil exposure must be seen against the normal mortality, which is on a colossal scale. Only a minute proportion of larval fish survive to an age when they reach a commercial size. Furthermore, most fisheries are based on fish of various ages, and if the size of one year-class is reduced, that is unlikely to have more than a marginal effect on the commercial catch. Calculations made by Johnston (1977) suggest that, making the most pessimistic assumptions, even a catastrophic oil spill (400,000 tons) in the North Sea would be responsible for a loss, from all causes, of 13,000 tons of fish. Since the annual commercial catch is 4.36 million tons, this shortfall would be hard to detect, particularly against the natural fluctuations in fish abundance. In fact, the only case in which an oil spill seems to have caused a shortage of finfish was following the wreck of the *Amoco Cadiz*, when the 1-year-old class of flatfish was thought to have been reduced (CNEOX, 1981).

SEA MAMMALS

There is remarkably little reliable information in the scientific literature on which to make an assessment of the threat of oil exposure to marine mammals. Most species appear to ignore floating oil and are unharmed when they encounter it.

Sea mammals include cetaceans (whales, porpoises, and dolphins), the tropical sirenians, seals and sea lions, sea otters, and, to a degree, polar bears. A number of land mammals (mink, rats, *etc.*) regularly forage on the shore and are in part dependent upon the sea.

Cetaceans and sirenians are entirely aquatic; seals, sea lions, and sea otters spend most of their time at sea but return to land at least for breeding; polar bears are primarily terrestrial mammals, but readily enter the sea.

All sea mammals are air-breathing and must surface from time to time, thus risking exposure to floating oil. Polar bears, other shoreline foraging mammals, and seals and their pups in the breeding colonies on shore are also at risk from stranded oil.

Most seals are colonial breeders and very large numbers may be exposed to a single oil slick that impacts a rookery. Cetaceans often travel in groups (pods) and numbers of them may encounter a single oil slick.

Effects of Oil

Sea otters and polar bears rely primarily upon their dense fur to provide thermal insulation. As with seabirds, if the pelage is matted with oil, water penetrates to the skin and the animals rapidly lose body heat. Kooyman *et al.* (1977) and Costa and Kooyman (1980) report a 5 to 10 percent decrease in subcutaneous temperature below experimentally oiled areas of fur and almost a doubling of the body metabolism to preserve body core temperature. Oil coating of isolated polar bear fur led to a tripling of conductance of heat across the skin (Hurst *et al.*, 1982; Oritsland *et al.*, 1981), and the effect was even greater in the presence of wind. Subcutaneous temperatures fell, and metabolic rate increased to preserve body core temperature, in the same way as in sea otters. Clearly, as with oiled seabirds, this situation, if prolonged, could lead to death from hypothermia. However, sea otters (Williams, 1978) and polar bears (Oritsland *et al.*, 1981; Engelhardt, 1981) readily groom oiled fur; and while this results in the ingestion of oil with undesirable consequences, it is likely that death from hypothermia can be avoided except for heavily oiled animals.

Other marine mammals rely upon a layer of subcutaneous fat (blubber) to provide thermal insulation and are not vulnerable in the same way. Oil adheres to the fur of seals but is readily washed off by immersion in the sea. The fur of ringed seals that had been experimentally exposed to crude oil for 24 hours was clean again within 24 hours after return to clean water (Smith and Geraci, 1975; Geraci and Smith, 1976), and 58 free-ranging elephant seal pups that had initially been more than 75 percent covered with oil were, with one exception, found to be clean one month later (Le Boeuf, 1971). Sea lions, walruses, and cetaceans have little or no body hair, and oil is unlikely to adhere to them, although the NRC (1985) report speculates that rugosities, roughened skin, and encrusting barnacles on some whales might provide a site for adhering oil.

Baleen whales feed by filtering plankton from the water; if oil is present, the baleen plates collect oil particles or become coated with oil. Accumulations of oil on bowhead baleen reduce its filtering efficiency by 10 percent when coated with Prudhoe Bay crude oil, and by 85 percent when coated with a waxier oil (Braithwaite, 1983). However, this accumulation is unlikely to be important in the long-term feeding strategies of baleen whales (Geraci and St. Aubin, 1982).

If sea mammals surface through an oil slick, the nostrils and eyes are likely to be coated with oil. The former is not a problem, but eye damage, such as conjunctivitis, has been reported in oiled seals (Smith and Geraci, 1975; Geraci and Smith, 1976; Nelson-Smith, 1970; Morris, 1970), although the condition is rapidly reversed. Eye damage is, in any case, common in natural populations of seals (King, 1964; Ridgway, 1972).

Avoidance of Oiled Waters

Captive bottle-nosed dolphins are able to detect and avoid oil on the water surface (Geraci *et al.*, 1983). However, there is abundant evidence that sea otters (Williams, 1978), seals

(Spooner, 1967), and a variety of cetaceans (Goodale *et al.*, 1981; Geraci and St. Aubin, 1982) do not actively avoid oil slicks, whether or not they have the ability to detect them.

Casualties In Oil Spills

Although Nelson-Smith (1970) reported the death of grey whales, a dolphin, northern fur seals, Californian sea lions, and northern elephant seals as a result of oiling following the Santa Barbara blowout, the link has been questioned by Simpson and Gilmartin (1970), Brownell and Le Boeuf (1971), and Le Boeuf (1971). Mortality of seals following oil spills has been attributed to the effect of oil on the coast of Wales (Davis and Anderson, 1976) and following the *Torrey Canyon* (Spooner, 1967), *Arrow* (Anon., 1970), and *Kurdistan* (Parsons *et al.*, 1980) oil spills, and an oil spill in the Gulf of St. Lawrence (Warner, 1969). It is possible, of course, that these attributions were correct, but in no case was the cause of death clearly established. The numbers of animals involved in all these instances were very small.

PELAGIC ENVIRONMENT

Plankton

Although the toxic components of petroleum oils can kill planktonic organisms, the losses are rapidly replaced by immigration from outside the affected area or by the reproduction of survivors, most of which have a short lifespan and a very high replacement potential. Because of the complexity of the planktonic ecosystem, its rapid changes, patchy distribution, and movement by water currents, it is impossible to detect more than very transient effects on plankton by even the largest and most damaging oil spills. There is no evidence that even these effects have any ecological significance.

Since plankton plays a critical role in most marine food chains, it is important to know the effect of oil spills on the planktonic community. Because the plankton occupies the upper layers of the sea, it is particularly exposed to toxic water-soluble elements leaching from floating oil as well as to microscopic droplets of emulsified oil. However, realistic study of the effect of oil on plankton is extremely difficult (Dicks, 1976; Colebrook, 1979), and most investigations have suffered from various disadvantages.

The planktonic ecosystem is very complex, containing as it does a large variety of single-celled plants (phytoplankton), many small crustaceans, the larvae of perhaps the majority of marine invertebrates as well as adults representing virtually all invertebrate groups, and the eggs and larvae of many fish species. Plankton is also very dynamic, with huge and rapid seasonal changes in species composition and the diurnal vertical migrations of many of the zooplankton (Davenport, 1982). It is also extremely patchy in its distribution (Cushing, 1953). All these factors make comprehensive field studies difficult.

Laboratory Studies. Toxicological studies in the laboratory have yielded little information that can be related to the consequences of oil spills for marine plankton. As Davenport (1982) points out, many of the organisms are small and delicate, and zooplankton species can show rapid changes of structure, physiological state, and nutritional requirements. Toxicological studies have therefore tended to focus on easily managed, robust species such as barnacle larvae, larger copepod species, fish eggs, or pure bacterial or algal cultures. It is unlikely that these are representative of a wider range of plankton species. Because of the rapid turnover of some of the species that have been used, or changing developmental stages of others, long-term exposure is generally impracticable and the experiments have therefore tended to be very short-term.

If the organisms are too varied to permit a 'representative' selection of species to be studied, the toxins in crude oil present a similar problem because they are equally varied. In most experiments, whole oil or water-soluble extracts are used and contain an unknown quantity of usually unknown and variable toxic constituents. Often, little regard is taken of the fact that crude oils from different oilfields differ greatly in their constituents. The alternative approach, that of using defined hydrocarbons in toxicity tests, gives greater precision but does not address the situation represented by an actual oil spill.

Crude oil and oil fractions are toxic to a variety of planktonic organisms. Oils with a high aromatic content are usually more toxic than others (Anderson *et al.*, 1977); weathered oil is much less toxic than fresh crude (Lee and Nicol, 1977); crude oils from different oilfields vary in their toxicity to developing eggs of cod, herring, and plaice (Kuhnhold, 1972). Lee and Nicol (1977) showed that coastal plankton is more resistant to fuel oil contamination than oceanic plankton. At low concentrations of petroleum hydrocarbons, below 30 to 50 ppb, photosynthesis is stimulated, presumably because of a nutritive effect; above 50 ppb it is progressively reduced (Gordon and Prouse, 1973). Feeding was depressed and food selection changed in two species of copepod at concentrations of about 250 ppb (Berman and Heinle, 1980). A variety of other sublethal effects have been recorded in zooplankton, but at concentrations close to lethal limits (Anderson *et al.*, 1977; Davenport *et al.*, 1979).

On the other hand, a number of planktonic crustaceans accumulate oil constituents rapidly from solution, evidently without coming to harm, and lose these contaminants when returned to clean water (Lee, 1975; Corner *et al.*, 1976). Parker *et al.* (1971) found that barnacle larvae and also a copepod, when maintained in a suspension of crude oil, swallowed droplets of crude oil which then appeared in the faeces, apparently unchanged, without harming these crustaceans.

Experiments with Large Enclosures. The acknowledged severe limitations of laboratory studies on marine plankton have led to the use of large enclosures in an attempt to bring greater realism to controlled experiments. These are large plastic enclosures ('big bags') of about 100 m³ capacity. These enclosures are anchored in sheltered waters and isolate the natural plankton community, which can then be subjected to appropriate experimental procedures under reasonably natural conditions. Several such enclosures were constructed in the Saanich Inlet, Vancouver Island, and Loch Ewe, Scotland (an issue of the *Bulletin of Marine Science*, Volume 27, Part 1, 1977, was devoted to an account of

the initial experiments, concerned with metal pollution, at both sites). Steele (1979), in a review of the achievements of such experimental ecosystems, says in summary that "the experiments conducted so far in large experimental ecosystems have probably taught us more about the general ecological interactions in such systems than about subtle long-term effects of pollutants."

Large experimental ecosystems offer substantial advantages over laboratory studies in that they contain a representative sample of the local plankton and permit interactions between different organisms in the planktonic ecosystem. The critical disadvantage is that by enclosing a section of the environment, horizontal movement of plankton is prevented, and that can be a critical departure from the natural situation, depending on local tidal flows and currents. The growth of organisms on the walls of the enclosure produces abnormal conditions at the periphery. While the larger the enclosure, the more realistic the conditions, the patchiness of plankton makes reliable sampling more difficult; furthermore, since large enclosures are very costly to build and maintain, fewer experiments can be carried out (Davenport, 1982).

In a series of Canadian experiments (Lee and Takahashi, 1977; Lee *et al.*, 1977), 10 ppb, 20 ppb, and 40 ppb of non-volatile hydrocarbons were added to enclosures. The lowest concentration had no effect, but at the two higher concentrations, there was a considerable increase in phytoplankton production and some change in species composition. There was a decline in the population of the diatom *Cerataulina* but a massive increase in the numbers of the micro-flagellate *Chrysochromulina* and also of the rotifers that feed upon it. The larger zooplankton species were unaffected.

Similar experiments, using a larger enclosure and an initial concentration of 100 ppb hydrocarbons of North Sea oil extract, were carried out in Scotland (Davies *et al.*, 1980). In this case, no effect on phytoplankton production or species composition was found, but copepod populations fell dramatically. This was due to a direct effect on the adults and also to the failure of eggs to develop.

Experience with Oil Spills. Toxicological studies and even experiments in large experimental enclosures give no realistic guidance as to the likely impact of an actual oil spill on the planktonic community. The enormous variety of organisms contributing to the community, the patchy distribution of them, and the rapid changes in species composition that occur, all make its study very demanding in manpower, resources, and time, so that field studies of acute impact on the plankton are rare and no definite statement can be made from them.

No effect on plankton was noted after the wreck of the *Torrey Canyon* (Nelson-Smith, 1970), the Santa Barbara blowout (Straughan, 1972), or the *Argo Merchant* oil spill (Kuhnhold, 1978), but these incidents were not followed by a detailed study of the plankton, and only gross changes are likely to have been detected.

A detailed study of plankton was made after the spillage of 1000 tons of No. 5 fuel oil from the tanker *Tsesis* in the northern Baltic Sea (Johansson *et al.*, 1980). Approximately 700 tons of the oil were collected, but the remaining 300 tons were deliberately left untreated

and the effects monitored for one month. Close to the wreck, where oil concentrations were highest, the zooplankton biomass declined dramatically, but it is not known if this was due to mortality or avoidance of the area. Substantial recovery occurred within 5 days. Phytoplankton biomass and productivity increased in the area, probably because of the absence of grazing zooplankton.

Following the *Amoco Cadiz* oil spill, which occurred on March 16, 1978, the composition of zooplankton in impacted coastal areas was normal in early April. The spring phytoplankton bloom appears to have been depressed; but by June no differences in population composition could be detected, possibly because of replenishment from outside the affected area (Laubier, 1978). The sheltered inlets ('abers') with low water exchange, which were heavily contaminated with oil, may have taken longer to recover.

BENTHIC ENVIRONMENT

Littoral Zone (Intertidal Zone)

For all shoreline types, biological recovery processes have been observed in the intertidal zone. The recovery processes occur concurrently with weathering of the oil, over periods of time that commonly range from 1 to 10 years. The time scale is influenced by shoreline characteristics (especially energy level and substrate grain size), oil type and concentrations, and the biological characteristics of the shore.

Several studies that have investigated longer-term effects of oil on a variety of shores are summarised in Table 7. In general, recovery from most oilings has been good within the time scale of 1 to 10 years. Within this time scale, rocky shores appear to recover more quickly than soft-sediment and salt-marsh shores. It is usual for exposed rocky shores to show good recovery within 2 years—the exception in Table 7 (Westwood *et al.*, 1989) concerns the more lengthy successional changes that occur after drastic cleaning. Sheltered sediment shores may retain oil to a much greater extent, and some reports (*e.g.*, Gilfillan and Vandermeulen, 1978; Krebs and Burns, 1978; see Table 7) show that recovery can take more than 6 or 7 years. Brittany salt marshes that were oiled following the *Amoco Cadiz* spill took 5 to 8 years to recover (Baca *et al.*, 1987). Variations within this time scale depend on marsh type, degree of initial oiling, and cleanup treatments.

Recovery may take longer than 10 years in exceptional circumstances, for example, if extensive asphalt pavements are present, or if relatively toxic oil becomes trapped in anaerobic sediments. Asphalt pavements are commonly 5 to 10 cm thick and 1 to 30 m wide; an exceptional one following the *Metula* spill was 400 m wide (Hann, 1977). Pavements develop a weathered crust, but the oil inside may remain relatively unweathered for long periods of time. The pavement provides a relatively stable substratum (in contrast to more mobile sand and gravel), and the weathered surface allows colonisation by algae and invertebrates, but this community is different from the 'normal' community for such a beach. Pavements are gradually eroded; they persist longest on the upper shore, where

they can constitute a physical barrier that restricts recolonisation by plants such as grasses and shrubs (Guzman and Campodonico, 1981).

Oil may be incorporated into anaerobic sediments, penetrating along pathways provided by the burrows of worms, molluscs and crustaceans, and the stems and root systems of marsh plants. Under normal conditions these pathways allow the penetration of oxygen into sediments that would otherwise be anaerobic. A possible problem following oiling is that there is subsurface penetration of oil, followed by death of the organisms that normally maintain the pathways. The pathways then collapse; e.g., burrows become filled in with sediment from the top if they are not actively maintained. Thus oil can be trapped in anaerobic sediment where its degradation rate will be very low, and organisms trying to recolonise may encounter toxic hydrocarbons. Under these conditions oil-tolerant opportunistic species are favoured, e.g., the worm *Capitella capitata*. The activity of such organisms helps the process of oil degradation, so that eventually more sensitive species can return, e.g., the fiddler crabs (Krebs and Burns, 1978).

Although long-term studies are incomplete, some authors have speculated concerning recovery rate; e.g., Conan (1982) suggests that as much as 30 years or 3 to 6 generations are required for recovery of a normal age distribution of clams. Another limitation of the available information, as pointed out by Vandermeulen (1982), is that only selected biological effects and recovery rates have been studied out of a very broad range of possibilities. For example, it is known that there is a dose-response relationship between aromatic hydrocarbons in mussel tissues and physiological responses such as feeding rate, respiration, and 'scope for growth' (Bayne *et al.*, 1982; Widdows *et al.*, 1987), but the ecological significance of these physiological changes in natural populations is not well-researched. These limitations in information should be borne in mind when considering overall recovery rates.

Two observations concerning the presence of residual oil as related to biological recovery can be extracted from Table 7. On the one hand, removal of oil by using drastic physical methods, beyond initial bulk oil removal, does not necessarily improve biological recovery times; on the contrary, it may prolong recovery (Baca *et al.*, 1987; Westwood *et al.*, 1989) if the cleanup removes living organisms and alters the habitat. On the other hand, the presence of residual oil does not necessarily prevent biological colonisation. For example, the growth of a number of organisms on asphalt pavement (Guzman and Campodonico, 1981) demonstrates the low toxicity of weathered residues. It may be justifiable to remove heavy deposits of oil where they have killed the underlying organisms and the shore is not being recolonised readily; a salt-marsh example is given by Guzman and Campodonico (1981). Transplants should be considered in such cases.

Animals with body burdens of hydrocarbons are likely to have measurable physiological changes, but they can survive and eventually depurate the hydrocarbons (Boehm *et al.*, 1982; Page *et al.*, 1987).

Different species may have different sensitivities and recovery times. For example, fucoid algae have been hardly affected by some oiling (e.g., Notini, 1978), possibly because of their mucilage coatings and the frequency of tidal washings. Salt-marsh plants such as

Spartina may be more sensitive because they have oleophilic cuticles and occur higher up the shore, where tidal washing is less prolonged. Different species may recolonise at different rates because of different mobilities or life cycles. An example is the recolonisation of the Fawley salt marsh, Southampton Water (a sheltered mud shore with high biological productivity), following improvements in refinery effluent quality. Both annual plants (notably *Salicornia*) and the perennial grass *Spartina anglica* recolonised sediments in which oil residues remained. However, the *Salicornia* spread much faster through tidal distribution of abundant seeds than the *Spartina* did with its relatively poor seed production and its slow vegetative recolonisation (Dicks and Levell, 1989).

There is also the question of the distance of the 'reservoir' of the recolonising species from the area to be recolonised. If this is great, as may be the case for rare species or if the spill is large and has affected many contiguous miles of coastline, then recolonisation times may be relatively long.

The season of the spill can affect recovery rates. For example, winter oiling of a salt marsh can affect seeds and reduce germination in the spring. Marked reduction of flowering can occur if plants are oiled when the flower buds are developing; even though there may be good vegetative recovery, there is a loss of seed production for that year (Baker, 1971).

Sublittoral Zone (Subtidal Zone)

Subtidal benthos may be impacted when oil is carried from the sea surface to the seabed adsorbed to particulates or by the re-distribution of oiled beach sediments. Impact on the subtidal benthos is usually less than on the shores and takes place after the initial intertidal impact as a result of the cushioning effect of the overlying water. Once the physical and direct toxic effects of the oil begin to decline, microorganism, meiofaunal and macrofaunal activities are able to utilise petroleum hydrocarbons as an energy source through a variety of pathways. Thus post-impact response can be typical organic enrichment where there is a population explosion of species able to use the increase in nutrients. Once the damaging effect of the oil is sufficiently reduced, the continuous nature of the marine environment ensures that eventual community recovery is inevitable. This usually takes 1 to 5 years.

There is a considerable body of information on the impact and recovery of intertidal benthos impacted by oil spills. Impact and recovery of the subtidal environment are less well studied largely because onshore impact causes more public concern and because of the direct physical impact, which causes an immediate and obvious effect. Although the overlying water column protects the subtidal benthos from physical impact, oil or its components may be carried to the seabed by a variety of means. In addition to the vertical mixing of the more water-soluble hydrocarbons into and throughout the water column, there is evidence that oil may be carried to the seabed by fine particulate matter. For example, estimates from sediment-trap data after the *Tsesis* spill in the Baltic Sea showed

that at least 20 tons of oil (equivalent to 0.5 g/meter²) reached the benthos in this way (Johansson *et al.*, 1980).

Oil may also directly come into contact with benthos through subsea leakage of installations such as storage facilities or pipelines and through natural seeps, the latter having been the subject of many studies of long-term effects of hydrocarbon contamination (Allen *et al.*, 1970; Spies and Davis, 1979; Davis and Spies, 1980; Kennicutt *et al.*, 1985; Hovland and Judd, 1988).

The other major source of oil on the seabed is from discharge of oil cuttings during offshore drilling operations (Davies *et al.*, 1984). Although, strictly speaking, this is not spilled oil, the large amount of accumulated information on the effects of hydrocarbon contamination could be useful in assessing the longer term recovery of oil-contaminated benthos.

The initial impact of a large oil spill on the subtidal benthos, as has been already said, will be cushioned by the overlying water, which has the effect of delaying the impact and reducing its intensity. A good illustration of this is the time lag between the impact of the *Florida* No. 2 fuel oil spill on the inshore fauna at Wild Harbor, Buzzards Bay, Massachusetts, and the fauna further offshore, which were affected a few days later as the oil gradually spread seawards (Sanders *et al.*, 1980).

Subtidal species vary in their sensitivity to oil. Some, like certain bivalves such as *Macoma balthica*, appear quite resilient to relatively high levels of petroleum hydrocarbons (Elmgren *et al.*, 1983). In contrast, certain crustaceans such as the Amphipoda appear to be particularly vulnerable. Huge populations of the amphipods *Apseudes*, *Bathyporeia*, and *Urothoe* were killed by the *Amoco Cadiz* oil spill in 1978 (Conan, 1982), with *Ampelisca* being later totally eliminated from the area (Cabioch *et al.*, 1980). Ampeliscids were also found to be particularly vulnerable to No. 2 fuel oil after the *Florida* spill at Buzzards Bay, Massachusetts, in 1969 (Sanders *et al.*, 1972). However, they were not the only susceptible species; within 48 hours of the oil's arrival in the bay, there were heavy mortalities of the benthos, including worms, other crustaceans, and fish which were up on the shores (Hampson and Sanders, 1969). Amphipods were again found to be amongst the most vulnerable species to oil pollution after the *Tsesis* spill, when two species, *Pontoporeia affinis* and *Pontoporeia femorata*, almost completely disappeared, together with the scaleworm *Harmothoe sarsi* (Elmgren *et al.*, 1983). In the Baffin Island Oil Spill Study at Cape Hatt, the amphipod *Gammarus setosus*, the only species severely affected by the experimental oil spill, washed up in the intertidal zone two days after oil had been introduced into the bay (Cross and Thomson, 1981, 1982).

There is evidence that where there is not a direct physical or acute toxic effect, the fauna may be indirectly killed by being driven from the protection of the sediment and then immobilised (Prouse and Gordon, 1976; Percy, 1976, 1977). For example, large numbers of subtidal heart urchins and razor clams were killed during the first weeks following the *Amoco Cadiz* spill when they were washed up onto the shore after leaving their burrows (Hess, 1978). During the Baffin Island oil spill study, sea urchins were observed feeding

on bivalves that had left their burrows and had been incapacitated by the oiling (Cross and Thomson, 1981).

The impact of an oil spill varies greatly with the nature of the spill, the nature of the receiving environment, and the type of biological community affected. The *Florida* oil spill (630 tons of No. 2 fuel oil) had a major impact on the benthos (Sanders *et al.*, 1980) as did the *Amoco Cadiz*, which released more than 230,000 tons of oil (Hess, 1978). In both cases weather conditions were such that the oil was directed shorewards into shallow water and ultimately onto the shore. In the case of the *Argo Merchant* oil spill (28,000 tons), wind prevented the oil from beaching (Grose and Mattson, 1977) and there was no significant impact on the benthos (Pratt, 1978). These two extremes serve to illustrate the importance of establishing the starting point when assessing recovery and the difficulty of generalising the process.

Probably the most detailed series of studies of benthic communities following an oil spill were those carried out after the *Florida* oil spill in Buzzards Bay, Massachusetts in 1969. (Hampson and Sanders, 1969; Sanders *et al.*, 1972; Michael *et al.*, 1975; Sanders, 1978; Sanders *et al.*, 1980). The faunal changes observed could be linked to the duration and severity of the oil dose and the extent of weathering. Following immediate effects of the oil impact, there was a reduction in the benthic fauna; opportunistic species such as the polychaete worm *Capitella* then dominated (Figure 9) and continued to do so for 11 months after the spill (Sanders *et al.*, 1972). The huge *Capitella* population was then rapidly replaced as the indigenous species of the area re-established themselves. This process continued over several years, but as late as 1974 the numbers of species had not reached those of the control area set up at nearby Sippewisset Marsh (Michael *et al.*, 1975).

Whilst the inshore area (Wild Harbor Bay) had been dominated by the worm *Capitella*, the offshore part of Buzzards Bay, Massachusetts, which later became contaminated by hydrocarbons spreading seawards, experienced a population explosion of a closely related species, *Mediomastus* (Figure 9). This worm underwent a sequence of events similar to that of its inshore counterpart, finally being replaced by the natural population as the oil contamination abated (Sanders *et al.*, 1980). Spies *et al.* (1988) draw attention to the similarity of this community response to the effects described by Pearson and Rosenberg (1978) for other sources of organic materials in the marine environment.

Most of the evidence cited by Sanders *et al.* (1980) suggests that the study sites furthest offshore had recovered within a year of the incident, with the shallower nearshore stations taking three or four years to approach normality.

A similar faunal response was elicited in tidal rivers after the *Amoco Cadiz* spill in which, at high oil concentrations, the benthic population of the impacted area was dominated by opportunistic polychaete worms. The species of the worms appeared to relate to oil concentration. Thus at concentrations of oil between 100 and 1,000 ppm, opportunists of the spionid and cirratulid worm families established themselves. At oil concentrations over 10,000 ppm, cirratulids and capitellids dominated (Glemarec and Hussenot, 1981).

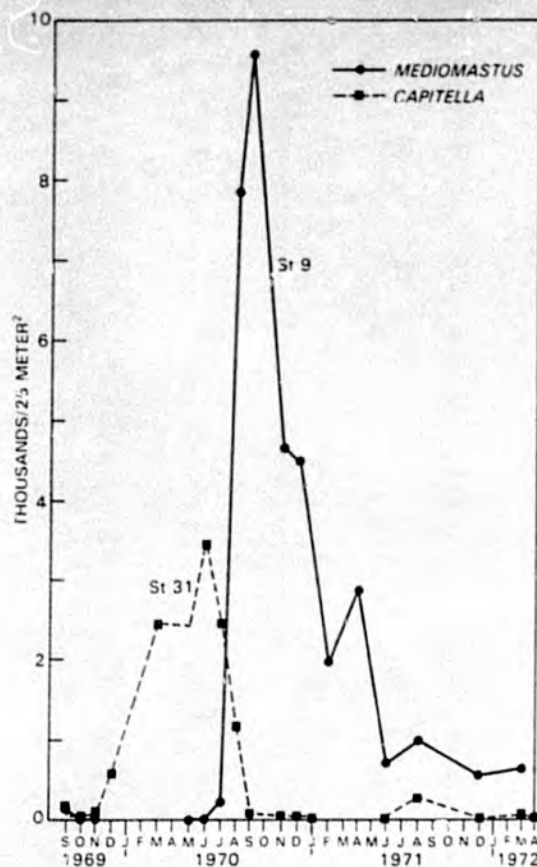


Figure 9: Succession of *Capitella* and *Mediomastus* nearshore (St 31) and offshore (St 9) after the Falmouth oil spill in Wild Harbor, Buzzards Bay, Mass. (Sanders *et al.*, 1980).

Although the presence of large numbers of opportunistic species clearly indicates highly disturbed environmental conditions, the increased total biomass that goes hand in hand with the increased numbers is indicative of enhanced productivity, the oil providing the source of organic enrichment. Similar community responses have been recorded where oily drill cuttings have been discharged (Davies *et al.*, 1984; Matheson *et al.*, 1986; Kingston, 1987). The occurrence of such opportunistic species under these circumstances may play a significant role in the active breakdown of the hydrocarbons.

Not all oil spills result in an obvious organic enrichment effect. Six years after the *Arrow* oil spill in Nova Scotia (1970), species diversity was still lower at oil-impacted sites than at the unoiled controls, and biomass was only one-third what it was at the controls (Thomas, 1978). Interestingly, however, populations of the lugworm *Arenicola* were more abundant in oiled sediments in 1976 than anywhere else in Nova Scotia (Gordon *et al.*, 1978). After the *Arco Anchorage* spill near Ediz Hook in Port Angeles in 1985, average total infaunal density, biomass, and diversity were highly variable over the shore and immediate sublittoral (Blaylock and Houghton, 1989). This variability persisted in the two years following the initial spill, although overall numbers of species and diversity increased over this time. Assessment of recovery at this site was complicated by the fact that the area was already under environmental stress from local industrial developments; however, the data

available have been interpreted as indicating that recovery was well under way by winter 1988 (Mancini *et al.*, 1989).

The vulnerability of certain species of Amphipoda to oil has already been discussed. The recovery process, once the physical and toxic effects of the oil ameliorate, will in the early stages be dominated by opportunistic species. Most benthic species that include a pelagic larval stage in their life cycle may be considered potentially opportunistic. The extent to which such species realise their potential will depend upon their ability to tolerate environmental insult and to out-compete other species.

The occurrence of nearby unaffected populations of organisms that are eliminated in a major spill is important if recovery is to be rapid. Thus where a species has been eliminated over an extended geographical area, as happened to the amphipod *Ampelisca* after the *Amoco Cadiz* spill, full recovery may be slow, but it is still achievable. In most cases there is a sufficient pool of adults nearby to provide a supply of larvae for rapid recruitment should the levels of oil concentration permit it. For example, in the summer following the *Arco Anchorage* spill, settlement of young bivalves was reported at several of the study sites that had previously been affected by the oil spill (Blaylock and Houghton, 1989). Recruitment after the *Tsesis* incident was not as immediate, but in one area the amphipod *Fontoporeia femorata*, which suffered heavy mortality at the time of the spill, had recovered to pre-spill values after about 9 months (Elmgren *et al.*, 1983).

Recently Dauvin and Gentil (in press) found that most of the pericarid amphipod populations that were suspected of having been irretrievably lost after the *Amoco Cadiz* spill in 1978 (Cabioch *et al.*, 1980) had completely recovered by 1988. Dauvin and Gentil (in press) also report the reestablishment of benthic communities in the Aber Wrac'h Channel, Bay of Morlaix, and Bay of Lannion of a similar specific composition and pattern of dominance as those found before the spill.

The *Tsesis* oil spill study (Elmgren *et al.*, 1983) is one of the few thorough sublittoral benthic studies carried out on a spill where dispersants were not used and there was good pre-spill information about the receiving environment. Figure 10 shows the number of individuals of benthos from two sites, one in the middle (Site 20) and one on the eastern part of the spill area. The figure demonstrates the natural variability of the benthic community data and allows it to be related to the impact of the oil spill and the return of the system (the picture is further complicated by the increasing eutrophication in the area resulting from nearby sewage input). One of the features of the community response to the spill was the survival of the bivalve *Macoma baltica* and the priapulid *Halicryptus spinulosus*; both animals have low mobility and both showed increased abundance after the spill. Although the impacted faunal community was recovering, Elmgren *et al.* (1983) claim that the dominance of *Macoma baltica*, a species with a long life span, will persist, maintaining a 'disturbed' community for several years and that 5 to 10 years may be needed for 'full recovery'.

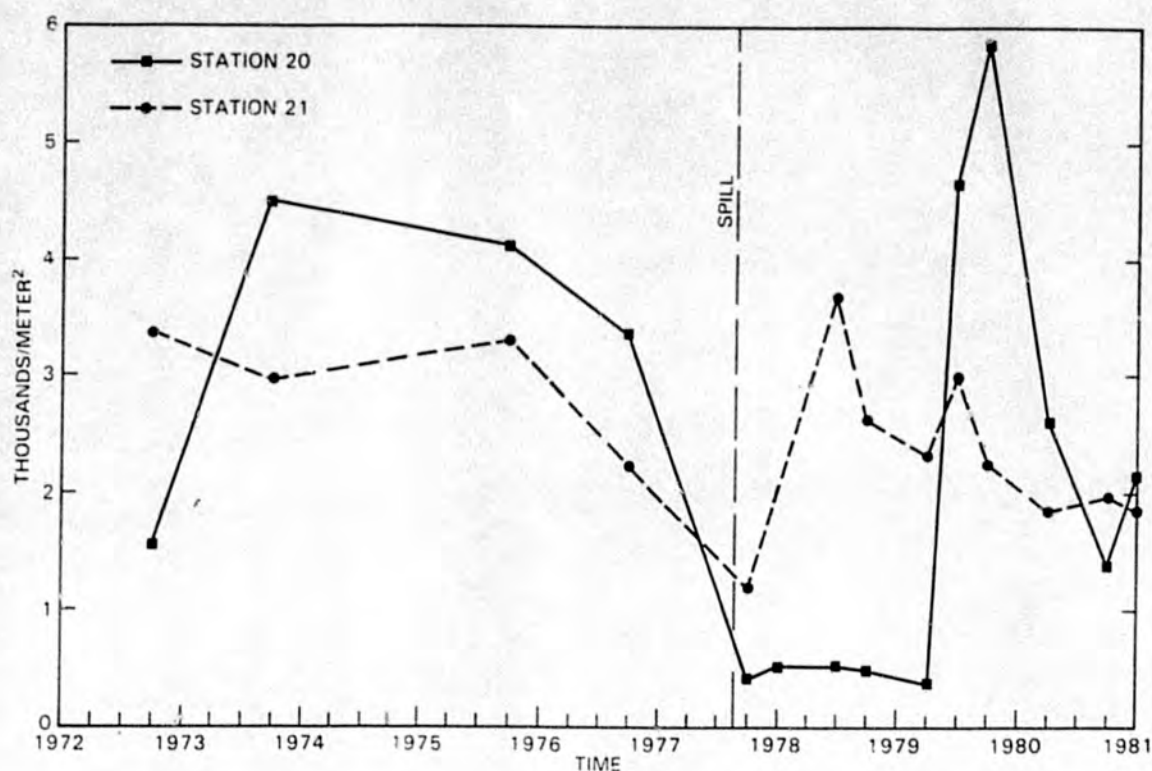


Figure 10: Changes in the faunal abundance at two localities affected by the *Tsesis* oil spill (Elmgren *et al.*, 1983).

There are few oil spill incidents where there has been no use of dispersants, no attempts to clean up, and no other anthropogenic activity. No cleanup effort was launched following the *Metula* spill in the Straits of Magellan. As has already been mentioned, hydrocarbons do, however, find their way to the seabed in other ways—through natural seepages and by deliberate discharge. Under these circumstances their presence on the seabed may be the only source of environmental disturbance.

The best known natural seepages are those that occur off the California coast, and these have formed the focus of many studies on hydrocarbon-based communities (Allen *et al.*, 1970; Straughan, 1976; Spies and Davis, 1979; Spies *et al.*, 1980; Davis and Spies, 1980). More recently, interest has been directed at hydrocarbon seeps in the North Sea (Hovland and Judd, 1988; Hovland and Thomsen, 1989).

Bacterial mats and other marine life associated with seepages were first studied by Spies and Davis (1979). Surveying oil and gas seeps near Santa Barbara, California, they found consistently greater densities of organisms around seep locations, compared with nearby areas. Where the seeps were particularly intense, the seabed was covered with white mats of the bacterium *Beggiatoa sp.* Similar mats have been found in the North Sea where the seepages are usually associated with pock marks caused by the sudden release of gas.

Beggiatoa sp. is known as an H_2S oxidiser that requires anaerobic conditions (Spies and Davis, 1979). It has been shown that there is a trophic pathway from petroleum oils through sulphate-reducing bacteria, to H_2S , to *Beggiatoa sp.*, to *Nematoda*, and thence other infauna (Spies and Des Marais, 1983). Similar *Beggiatoa sp.* mats have been observed associated with oily cuttings piles discharged onto the seabed during offshore drilling operations (Gillam *et al.*, 1986) together with greatly enhanced numbers of opportunistic species (Matheson *et al.*, 1986; Kingston, 1987; Mair *et al.*, 1987). These blooms of species, which often include *Capitella* (see Figure 11), are very similar to those recorded for spills such as the *Florida* (Sanders *et al.*, 1980), and it is tempting to draw parallels.

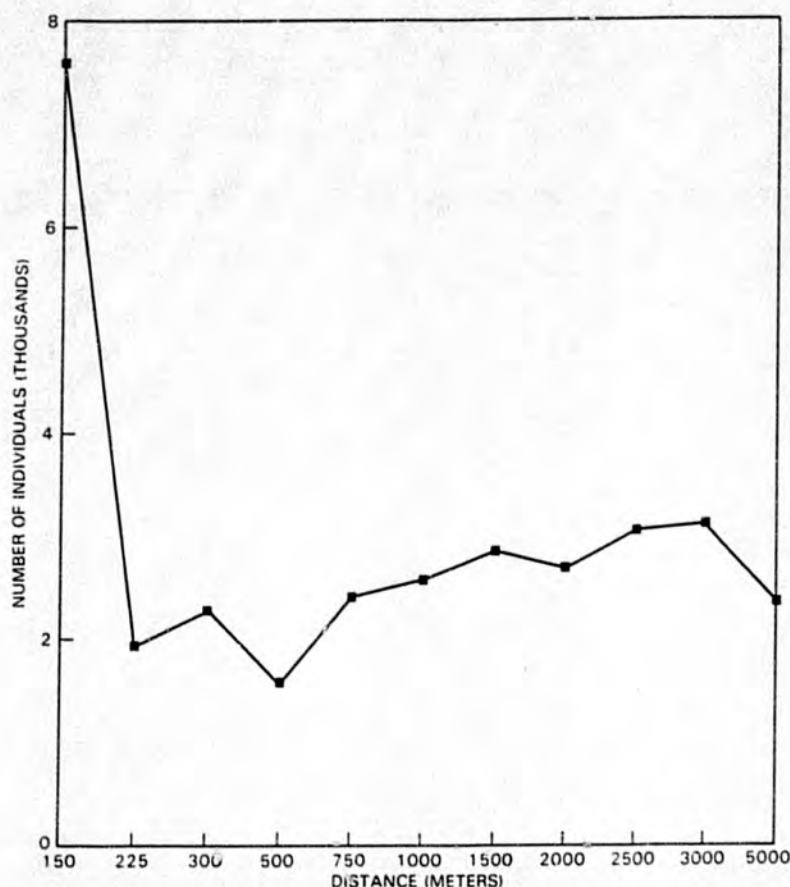


Figure 11: Changes in the number of individuals with increasing distance from the Statfjord Bravo production platform, 1984 (Matheson *et al.*, 1986).

Although there are no reports in the literature of subtidal *Beggiatoa sp.* mats associated with oil spills, it is likely that processes similar to those described above take place. Certainly elevated numbers of nematodes are a feature of many faunal responses to an oil spill. Large nematode populations were reported after the *Amoco Cadiz* spill (Chassé, 1978), and nematodes have been found to maintain substantial populations after spills such as that of the *Tsesis* (Elmgren *et al.*, 1983), and the *Venpet* and *Venoil* spills in South Africa (Fricke *et al.*, 1981).

It is apparent that once the physical and direct toxic effects of the oil begin to decline, microorganism, meiofaunal, and macrofaunal activities are able to utilise petroleum hydrocarbons as an energy source through a variety of pathways (Knap *et al.*, 1979; Spies and Des Marais, 1983). The implication of this is that high faunal abundance under these conditions indicates more active biodegradation of the hydrocarbons than if the fauna were impoverished.

ACKNOWLEDGMENTS

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TABLE 1

Examples of Background Concentrations* of Hydrocarbons in Water

Location	Hydrocarbon Type and Concentration	Reference
Ocean waters throughout the world	Most surface and near surface waters have 1–10 ppb total hydrocarbons. Both biogenic and petroleum hydrocarbons appear to be ubiquitous.	Myers and Gunnerson (1976)
Baffin Bay and eastern Canadian Arctic	Floating particulate residues rare. Extractable residues in surface microlayer 3–1726 ppb and in water column 0–87.5 ppb (solvent = CC1 ₄).	Levy (1981)
Arctic Ocean north of Svalbard	Total hydrocarbons (THC's) in surface water under ice, 0.1–0.6 ppb Kuwait crude oil equivalents with respect to light molecular weight compounds and 0.05–0.2 ppb with respect to heavy molecular weight compounds.	Fogelqvist <i>et al.</i> (1982)
UK marine waters (North Sea, English Channel and Irish Sea)	Total hydrocarbons (THC's) at 1 m, 1.1–74 ppb Ekofisk crude oil equivalents, all values greater than 3.5 ppb occurring inshore. Mean THC's offshore 1.3 ppb N. North Sea, 1.5 ppb W. Channel, 2.5 ppb E. Channel and S. North Sea, and 2.6 ppb Irish Sea.	Law (1981)
Northern North Sea	THC's at 1 m, 1978 'clean' station at least 80 km from land or from oil platform, 7.2 ppb. 1980 clean stations within 25 km of oil activity, 1.2–2.4 ppb. Outer Forth 7.4 ppb, mid Forth 9.4 ppb, inner Forth 23.2 ppb. Total aryl hydrocarbons at 1 m, 3.2 to 32 km east of Brent 0.032–0.109 ppb; outer Forth 0.064 ppb; mid Forth 0.064 ppb; inner Forth 0.042 ppb.	Massie <i>et al.</i> (1985a)
English Channel	THC's at 1 m, less than 0.3–14 ppb Ekofisk crude oil equivalents. The higher concentrations were in Southampton Water and to the S and E of the Isle of Wight (higher shipping activity).	Fileman and Law (1988)
Southern Baltic Sea	THC's at 10 m, Slupsk (offshore) 2.0 ppb Ekofisk crude oil equivalents, Gdansk basin (offshore) 34 ppb, Puck Bay (inshore) 130 ppb.	Law and Andrulewicz (1983)
Southern Baltic Sea	C15–C32 n-alkanes at 0 m, 9–1744 ppb, C15–C32 n-alkanes at 5 m, 10–219 ppb, benzo(a)pyrene at 0 m, 0.03–2.9 ppb, benzo(a)pyrene at 5 m, 0.04–3.1 ppb.	Grzybowski <i>et al.</i> (1987)
Southern Baltic Sea	Total polycyclic aromatic hydrocarbon (PAH) compounds (sum of 11 PAH) at 9 m, 9–143 ppb. Total PAH at 5 m, 10–180 ppb.	Lamparczyk <i>et al.</i> (1988)

* All concentrations have been converted to ppm or ppb from the reported values. A water density of 1 gram/cc has been assumed.

TABLE 2

Examples of Background Concentrations* of Hydrocarbons in Sediments

Location	Hydrocarbon Type and Concentration	Reference
Baffin Bay and eastern Canadian Arctic	Extractable residues 1-41 ppm. Solvent CC1 ₄ .	Levy (1981)
Gulf of Maine	16 polycyclic aromatic hydrocarbon (PAH) compounds, total concentrations 10-512 ppb (dry weight). These concentrations are an order of magnitude lower than those observed in the coastal zone, but higher than those on Georges Bank.	Larson <i>et al.</i> (1986)
Boston Harbour	14 PAH compounds, total concentrations 483-718,364 ppb (dry weight). The highest concentrations from the inner harbour almost an order of magnitude higher than previously reported concentrations from a range of urban estuaries.	Shiaris and Jambard-Sweet (1986)
Narragansett Bay	Alkanes and aromatics. 50-120 ppm south, 130-440 ppm central, 500-700 ppm north.	Farrington and Quinn (1973)
UK marine sediments	THC's (Ekofisk crude oil equivalents) 0.27-340 ppm, with the highest concentration being in the entrance to the Mersey.	Law (1981)
English channel	THC's (Ekofisk crude oil equivalents) dry mass, 0.3-5.60 ppm. Highest in Southampton Water.	Fileman and Law (1988)
Milford Haven and Daucledau, SW Wales (subtidal)	THC's (ppm) commonly 100-300 up to 700. Contaminants concentrated in areas of fine sediment (high in organic and clay content).	Little and McLaren (1989)
Milford Haven (Angle Bay intertidal), SW Wales	THC's (ppm dry weight) in fine sand (0-5 cm layer), 18-70.	Howard <i>et al.</i> (1989)
Danish marine sediments	Alkanes and aromatics. 5-390 ppm Danish coast, 46-1800 ppm Copenhagen Sound.	Jensen (1981)
Southern Baltic Sea	THC's (Ekofisk crude oil equivalents) dry mass, 4.0-140 ppm, with the highest concentration occurring in the Gotland and Gdansk basins.	Law and Andrulewicz (1983)
Southern Baltic Sea	C15-C32 n-alkanes, 626-23,040 ppm benzo(a)pyrene, 2-49 ppm, with the highest concentrations occurring in Gdansk and Pomerania Bays.	Lamparczyk <i>et al.</i> (1988)

* All concentrations have been converted to ppm or ppb from the reported values.

TABLE 3

**Examples of Background Concentrations* of Hydrocarbons
in the Tissues of Mussels**

Location	Hydrocarbon Type and Concentration	Reference
Northeast Gulf of Alaska	17.6 ppm dry mass Unresolved Complex Mixture (UCM).	Wise <i>et al.</i> (1980)
Yaquina Bay, Oregon	Total concentrations of 15 polynuclear aromatic hydrocarbons (PNAH) measured. Average 986.2 ppb in industrialized area, 273.9 ppb in more remote area.	Mix and Schaffer (1983a)
Gulf of St. Lawrence	Most concentrations of benzo(a)pyrene below detection limit; high concentrations of 24 and 28.5 ppb (dry mass) at mouth of Saguenay Fjord.	Picard-Berube and Cossa (1983)
Various U.S. mussel watch stations	3-298 ppm dry mass UCM.	Farrington <i>et al.</i> (1980)
Scottish coast	Average of 109 ppb PNAH from 'clean' (sparsely populated) sites, 1127 ppb from industrialized sites.	Mackie <i>et al.</i> (1980)
N. Sea oil production platform	46-77 ppm dry mass UCM.	Rowland and Volkman (1982)
Copenhagen Sound	800-3500 ppm dry mass THC (calculated from micrograms per gram of lipid, assuming 8% lipid in body tissues).	Jensen (1981)

* All concentrations have been converted to ppm or ppb from the reported values.

TABLE 4
Residence Times of Oil on Shores

Shore Type	Location	Oil	Residence Time	Reference
Steep exposed bedrock	Hurlstone Point, SW England	Experimental application of Forties crude	40-50% cover remained after 11 days; thin brown stain remained after 1 month.	Baker <i>et al.</i> (1984)
Steep exposed bedrock	Hurlstone Point, SW England	Experimental application of Flotta residue and mousse	Most mousse washed off after 2 tidal immersions; most residue was washed off after 6 immersions.	Baker <i>et al.</i> (1984)
Exposed rock platform just above high water	Near East Prawle, Devon, England	Spots of oil thrown up by spray	Shrinkage of oil patches after 1.2-3.3 years, thinning after 1.9-5.3 years, varying with type and thickness of oil. Maximum duration of oil spots on this shore 17-18 years.	Mottershead (1981)
Rock reef	Godrevy Point, Cornwall, SW England	Kuwait mousse from the <i>Torrey Canyon</i> spill, 1967 (no direct dispersant use on this moderately oiled shore)	Traces of oil visible 1 year after, no visible oil 2 years after.	Southward and Southward (1978)
Rock platform	Watchet, Somerset, SW England	Experimental application of Forties crude	40-50% cover remained after 11 days, no visible oil after 1 month.	Baker <i>et al.</i> (1984)
Exposed beach of mobile sand and shingle	Corton, E England	Heavy fuel oil and mousse from <i>Eleni V</i> spill, 1978	Mechanical clearance of surface oil and massive resorting of beach material during winter storms left beaches visually clean after 1 year, except along tide lines. Hydrocarbon concentrations in inshore water and mussels returned to background levels about 2 years after the spill.	Blackman and Law (1980a) Blackman and Law (1980b) Blackman and Law (1981)

TABLE 4 Continued

Shore Type	Location	Oil	Residence Time	Reference
Exposed sand and gravel beach	Queen Charlotte Islands, Canada	Spill of diesel fuel and gasoline	Traces of fuel remained within 300 m of the spill site after 60 days.	McLaren (1985)
Variety of shores	Brittany	Light Arabian and Iranian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	Exposed rocky coasts and wave-cut platforms were cleaned of very heavy doses of oil within a few days. Oil penetrated deeply (30 cm) into gravel beaches.	Hayes <i>et al.</i> (1979)
Variety of shores	Brittany	Light Arabian and Iranian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	2 years after, oil persisted primarily as tar blotches and black staining along exposed rocky shores and as oil-contaminated interstitial water in intertidal flats.	Gundlach <i>et al.</i> (1981)
A variety of shores along the Pink Granite coast	Brittany	<i>Amoco Cadiz</i> (1978) and subsequent spills	Contribution of remaining weathered residues of <i>Amoco Cadiz</i> oil to the hydrocarbon baseline was small in 1985 (7 years after the spill) compared with more recent inputs.	Page <i>et al.</i> (1988)
Variety of shores in small bay	British Columbia	No. 5 fuel oil from the <i>Irish Stardust</i> spill, 1973	After 4 years, no oil on stone, gravel residues and sand. UCM in sediment extracts.	Cretney <i>et al.</i> (1978)
Variety of shores in bay	Chedabucto Bay, Nova Scotia	Bunker C fuel oil from the <i>Arrow</i> spill, 1970	After 6 years, only a few locations visibly contaminated with large quantities of oil identifiable as <i>Arrow</i> Bunker C. These were upper high tide zones on 3 islands, where an oil/sediment pavement remained.	Keizer <i>et al.</i> (1978)

TABLE 4 Continued

Shore Type	Location	Oil	Residence Time	Reference
Sand/gravel/cobble beaches, often with low tide terraces, wide range of energy levels	Straits of Magellan	Arabian crude and mousse from the <i>Metula</i> spill, 1974	12 years after, remaining oil was mainly a narrow strip that was laid down by high spring tides. Major exception in Puerto Espora area where extensive asphalt pavements remained in intertidal and supratidal areas over shoreline length of several km. Surface of pavements with weathered crust, but oil within of low viscosity in many cases (early post-spill descriptions for comparison).	Owens <i>et al.</i> (1987a, b) Baker <i>et al.</i> (1976); Hann (1977)
Sheltered beach of sand, shingle and rocks	Lowestoft harbour, E England	Heavy fuel oil and mousse from <i>Eleni V</i> spill, 1978	Very little change in appearance and composition of oil after 1 year; still little change after 2 years under a surface crust of weathered oil.	Blackman and Law (1980a) Blackman and Law (1981)
Range of beaches	Cape Hatt, Baffin Island	Experimental application of aged Lagomedio crude (BIOS programme), 1981	On exposed beach, 99% of oil removed within 48 hours. On partially exposed beach, most oil removed within first open water season of 6-8 weeks. With sheltered beaches, cleaning rate was slower on pebble/cobble beach than on flatter fine-grained beach.	Sergy (1985)
Range of sediment shorelines	Wales and SW England	Experimental applications of Nigerian crude	Residence times ranged from 3 days to more than 1 year, depended upon energy level, drainage, and sediment textural gradients.	Little and Scales (1987) Little (1987)

TABLE 4 Continued

Shore Type	Location	Oil	Residence Time	Reference
Sheltered gravel beach	Cape Hatt, Baffin Island	Experimental application of aged Lagomedio crude	Initial volume of oil retained on beach (5.3 m ³) reduced to 1.3 m ³ after 4 years. Nearly 30% of this was in an asphalt pavement, relatively unweathered.	Owens <i>et al.</i> (1987)
Sheltered beach	Cape Hatt, Baffin Island	Experimental application of aged Lagomedio crude	Over a 4-year period, migration of oil from the beach into nearshore subtidal sediments.	Owens <i>et al.</i> (1987)
Intertidal sand flat	Willapa Bay, Washington	Experimental application of North Slope crude	Fauna (mainly burrowing crustaceans) capable of introducing measurable amounts of oil into the subsurface, where it was retained long after the rest of the stranded oil had washed away.	Clifton <i>et al.</i> (1984)
Simulated intertidal flat conditions	Laboratory experiments (OILME) project	Experimental applications of weathered crude	Results show that there is greater retention with greater loading thicknesses, with longer sediment emergence periods and with lower mud content.	Harper <i>et al.</i> (1985)
Lower shore sediments, relatively low energy	Baie Verte Newfoundland	Spill of diesel oil, 1982	Relatively high concentration of aromatics still present after 27 months. After 39 months no PAHs found except fluorene.	Kiceniuk and Williams (1987)
Low-energy beach of pebbles and sand	Spitzbergen	Spill of diesel oil, 1978	High concentrations of oil in sediment 2 years after spill.	Gulliksen and Taasen (1982)
Sandy pocket beach	Long Cove, Nova Scotia	Experimental application of Scotian Shelf condensate (1982)	C8 hydrocarbons present after 3 months in upper intertidal surface sand. No loss of volatiles over 6 months in subsurface sand from upper and middle intertidal.	Strain (1986)

TABLE 4 Continued

Shore Type	Location	Oil	Residence Time	Reference
Sandy beaches	Brittany	Oil/mousse from the <i>Amoco Cadiz</i> , 1978	After 3 years, oil in discrete layers 1-2 cm thick persists in several beaches. These can migrate downwards, as far as the water table.	Long <i>et al.</i> (1981)
Low-energy fine sediments	Long Cove, Searsport, Maine	Jet fuel and No. 2 heating oil spill from fuel depot, 1971	5 years after spill, area estimated to contain roughly 20% less oil than in 1971.	Mayo <i>et al.</i> (1978)
Gently sloping shoreline of low-energy lagoon	Chedabucto Bay, Nova Scotia	Bunker C fuel oil from the <i>Arrow</i> spill, 1970	Stranded oil persists after 7 years, continuously leaching into beach substrate where weathering occurs throughout the top 15 cm.	Vandermeulen <i>et al.</i> (1977)
Salt marsh	Milford Haven, SW Wales	Heavy fuel oil spill, oil up to 5 cm thick stranded, 1969	Oil has persisted for 18+ years with little diminution (protected by a layer of post-spill sediment).	Baker <i>et al.</i> (1989)
Salt marsh	Brittany	Crude oil remaining after <i>Amoco Cadiz</i> cleanup (1978)	Nuisance amounts of oil remained 5 years after.	Seip (1984)

TABLE 5

**Summary of Shoreline Classification in Order of Increasing
Vulnerability to Oil Spill Damage (Gundlach and Hayes, 1978)**

Vulnerability Index	Shoreline Type	Comments
1	Exposed rocky headlands	Wave reflection keeps most of the oil offshore—no cleaning necessary.
2	Eroding wave-cut platforms	Wave-swept; most oil removed by natural processes within weeks.
3	Fine-grained sand beaches	Oil does not usually penetrate far into the sediment, facilitating mechanical removal if necessary; otherwise, oil may persist several months.
4	Coarse-grained sand beaches	Oil may sink and/or be buried rapidly, making cleanup difficult; under moderate- to high-energy conditions, oil will be removed naturally within months from most of the beach face.
5	Exposed, compacted tidal flats	Most oil will not adhere to, nor penetrate into, the compacted tidal flat; cleanup usually unnecessary.
6	Mixed sand and gravel beaches	Oil may undergo rapid penetration and burial; under moderate- to low-energy conditions, oil may persist for years.
7	Gravel beaches	Same as Index 6; a solid asphalt pavement may form under heavy oil accumulations.
8	Sheltered rocky coasts	Areas of reduced wave action; oil may persist for many years. Cleanup is not recommended unless oil concentration is very heavy.
9	Sheltered tidal flats	Areas of low wave energy and high biological productivity; oil may persist for many years. Cleanup is not recommended unless oil accumulation is very heavy. These areas should receive priority protection by using booms or oil-sorbent materials.
10	Salt marshes and mangroves	Most productive of aquatic environments; oil may persist for many years. Cleaning of salt marshes by burning or cutting should be undertaken only if heavily oiled.

TABLE 6
Microbial Degradation

Site/Samples	Hydrocarbons	Observations on Microbial Degradation	Reference
Shallow and deep water sediments, Chedabucto Bay, Nova Scotia	Bunker C fuel oil from the <i>Arrow</i> spill, 1970	In July and November 1970, hydrocarbon utilising microorganisms (HCUs) comprised up to 15% of the total population. In 1971 and 1972, HCU numbers at around 1%, a value obtainable routinely in 'clean' areas. In 1976 comparable with 1972/1972-77 out of 79 samples were comparable to areas described as 'clean'.	Stewart and Marks (1978)
Lugworm bed sediments, Black Duck Cove, Nova Scotia	Bunker C fuel oil from the <i>Arrow</i> spill, 1970	Hydrocarbon concentrations were substantially lower in worm casts than in initial sediment. This loss can be accounted for by microbial degradation, which is stimulated by the worms' activity.	Gordon <i>et al.</i> (1978)
Beaches in the Straits of Magellan	Light Arabian oil/mousse from the <i>Metula</i> spill, 1974	Oil degradation proceeded relatively slowly, with marked persistence of oil 2 years after the spill. Experimental work suggested that the limiting factors were low concentrations of nitrogen and phosphorus and the inaccessibility of hydrocarbon components inside asphalt-like concretions. Temperature did not seem to be a limiting factor.	Colwell <i>et al.</i> (1978)
Ile Grande marshes, Brittany	Light Arabian and Iranian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	Evolution of hydrocarbons studied 1978-1980. Biodegradation important in superficial sediments, with preferential degradation of n-alkanes. Aromatics seemed not to have altered after 3 years. Degradation of percolated hydrocarbons slower than in surface layer. Numbers of degrading bacteria decreased when n-alkanes disappeared.	Mille <i>et al.</i> (1984)
Aber Benoit estuary, Brittany	Light Arabian and Iranian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	By 1986, all but the most heavily oiled locations had assemblages of biogenic hydrocarbons similar to the reference sites. Measurable residues of weathered <i>Amoco Cadiz</i> oil remained only in isolated soft sediment locations serving as repositories for fine sediment from other parts of Aber Benoit. These predicted to reach a background state as microbial activity continues to degrade any petroleum fractions remaining.	Page <i>et al.</i> (1989)

TABLE 6 Continued

Site/Samples	Hydrocarbons	Observations on Microbial Degradation	Reference
Nearshore sediments (top 5 cm) of Beaufort Sea. Ice-free, -1.8°C year-round	Experimental application of Prudhoe Bay crude	Studies for 2 years. Oil degraded slowly; only after 1 year's exposure was biodegradation evident. Aliphatic compounds were not preferentially degraded over aromatics. C17 and lower molecular weight alkanes were preferentially degraded over high molecular weight alkanes.	Haines and Atlas (1982)
Estuarine sediments, Brittany	Experimental applications of Arabian light crude	As long as the amounts of oil remained higher than a threshold value, biodegradation was inhibited, presumably due to oxygen and/or nutrients limitation.	Fusey and Oudot (1984)
Samples of water and sediments from North Sea oilfields	Experimental additions of aromatic hydrocarbons	Microorganisms in the samples had the potential to degrade smaller aromatic hydrocarbon molecules rapidly. Degradation of larger aromatic molecules as exemplified by benzo(a)pyrene was minimal.	Massie <i>et al.</i> (1985b)
Seaweed heaps on Arctic and sub-Arctic shores	Experimental applications of weathered Statfjord crude	In Norway (subpolar and temperate), biodegradation of oil in heaps requires artificial supply of oxygen, as heaps become anoxic within days under normal conditions. Seaweed heaps in Arctic Spitzbergen provided more favourable conditions for oil biodegradation, because of more heterogeneous conditions in terms of oxygen availability.	Sveum and Sendstad (1985)
Intertidal mud, Jadebusen, W Germany	Experimental applications of Statfjord crude (<i>in situ</i> and with mud samples in laboratory)	Aerobic mud was highly active in hydrocarbon biodegradation. Anaerobic experiments confirmed the common experience of low or zero rates. Hydrocarbons in an adsorbed state are more easily biodegradable than as a floating layer or droplets.	Hopner <i>et al.</i> (1987)

TABLE 7
Recovery of Littoral Benthos

Shore Type	Location	Oil	Observations on Recovery	Reference
Rock reef	Godrevy Point, Cornwall, SW England	Kuwait mousse from the <i>Torrey Canyon</i> spill, 1967 (no direct dispersant use on this moderately oiled shore)	Good recovery after 2 years.	Southward and Southward (1978)
Rock shelf	NW coast of the State of Washington	Navy Special fuel oil from <i>General MC Meigs</i> spill, 1972	Effects on urchins and algae for at least 1 year. No marked long-term effects on community balance. Hydrocarbon residues present in mussels after 5 years; attributed to recontamination by winter discharges from wreck.	Clark <i>et al.</i> (1978)
Rock/boulders/cobbles	Sullom Voe, Shetland	Heavy fuel oil from the <i>Esso Bernicia</i> spill, 1978	9 years after, 5 km of shore still showed successional changes (resulting mainly from use of bulldozers in cleanup).	Westwood <i>et al.</i> (1989)
Rock/boulders/cobbles	Sullom Voe, Shetland	<i>Esso Bernicia</i> oil and subsequent inputs	Winkles <i>Littorina littorea</i> collected 1981 had significant enzyme changes indicating lysosomal destabilization.	Moore <i>et al.</i> (1982)
Exposed rock	Hurlstone Point, N Somerset, England	Experimental applications of Forties crude, 1979	Reductions in limpets and small littorinid winkles during the year following treatment.	Crothers (1983) Baker <i>et al.</i> (1984)
Exposed rock	Hurlstone Point, N Somerset, England	Experimental applications of Flotta residue and mousse, 1981	Only significant change after 6 months was an increase of colonisation by barnacle larvae in oiled plots.	Baker <i>et al.</i> (1984)
Rock platform	Watchet, N Somerset, England, 1979	Experimental applications of Forties crude	Main change in all plots including controls was increase of furoid algae, interpreted as a continuation of a long-term trend.	Baker <i>et al.</i> (1984)

TABLE 7 Continued

Shore Type	Location	Oil	Observations on Recovery	Reference
Rocky shores	Swedish archipelago, Baltic Sea	No. 5 fuel oil and some bunker oil from the <i>Tsesis</i> spill, 1977	Dominant alga <i>Fucus vesiculosus</i> not affected. Funal density within algal zone was 8-10% of previous level 2 weeks after spill. Recovery began within 2 months, with normal densities after 1 year at some sites. Recovery varied depending on severity of oiling and species involved. After 1 year hydrocarbon concentrations in mussels approached normal conditions except at the most heavily oiled sites, though there were still elevated levels of substituted naphthalenes.	Notini (1980) Linden <i>et al.</i> (1979) Boehm <i>et al.</i> (1982)
Rocky shores	Åland, Finland, Baltic Sea	Crude oil from the Soviet tanker <i>Antonio Gramsci</i> , 1979	By 4 months after spill there was new settlement of barnacles and mussels close to remaining oil on rocks. Little difference between oiled and non-oiled areas in <i>Cladophora</i> belt; in <i>Fucus</i> belt there was some decline in mussels and mobile crustaceans.	Bonsdorff (1981)
Rocky, moderately exposed shore	W coast of Norway	Iranian crude oil from 1976 spill	13 months after spill, significant amounts of hydrocarbons remained in winkles <i>Littorina littorea</i> . No detectable effects on fertilization, but hatching success significantly less in oiled population.	Staveland (1979)
Beaches with sand, stones and rock	Gastviken Bay, Musko Island, Baltic Sea	Medium and heavy fuel oil from the <i>Irini</i> spill, 1970; mechanical cleanup	No oil-associated effects on <i>Fucus vesiculosus</i> ; severe initial depletion of fauna. Recolonisation by most species occurred within 1 year, but low population densities during the 2nd year. After 4 years, no significant evidence of lasting detrimental effects, when natural annual variations taken into account.	Notini (1978)

TABLE 7 Continued

Shore Type	Location	Oil	Observations on Recovery	Reference
Variety of shores in bay	Chedabucto Bay, Nova Scotia	Bunker C fuel oil from the Arrow spill, 1970	6 years after, lower diversity, lower biomass of flora, smaller clams (<i>Mya</i>) and larger winkles (<i>Littorina</i>) at oiled sites compared with controls. Abundant lugworms (with elevated hydrocarbon concentrations) in oiled sediments.	Thomas (1978) Gordon <i>et al.</i> (1978)
Variety of shores in bay lagoons	Chedabucto Bay, Nova Scotia	Bunker C fuel oil from the Arrow spill, 1970	<i>Mya</i> remained under continued stress in oiled lagoons 6 years after spill.	Gilfillan and Vandermeulen (1978)
Variety of shores	Straits of Magellan	Light Arabian oil/mousse from the <i>Metula</i> spill, 1974	1977 data suggested continuing impact in areas still heavily oiled, and recovery of invertebrates in areas which had lost oil.	Straughan (1978)
Variety of shores	Straits of Magellan	Light Arabian oil/mousse from the <i>Metula</i> spill, 1974	Asphalt pavement recolonised by algae and (more slowly, from lower intertidal levels) animals, mainly mussels and the gastropod <i>Siphonaria lateralis</i> . 5 years after spill, community still relatively simple in composition.	Guzman and Campodonico (1981)
Variety of shores	Straits of Magellan	Light Arabian oil/mousse from the <i>Metula</i> spill, 1974	Persistent effects on flora and insect fauna of heavily oiled salt marsh.	Guzman and Campodonico (1981)
Variety of shores	Brittany	Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	Marshes severely affected, with no recovery in 2 years at the most heavily oiled sites. 5 years after, Cantel marsh which was oiled but had no cleanup was essentially restored by natural processes. 8 years after, the Ile Grande marsh which had heavy cleanup was well recovered, facilitated by artificial plantings.	Gundlach <i>et al.</i> (1981) Baca <i>et al.</i> (1987)

TABLE 7 Continued

Shore Type	Location	Oil	Observations on Recovery	Reference
Variety of shores	Brittany	Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	9 months after, hydrocarbons from the spill identified in limpets from rocky shores and <i>Mya</i> from mud flats. Heavier molecular weight aromatics present in <i>Mya</i> , not in limpets.	Vandermeulen <i>et al.</i> (1981)
Variety of shores	Brittany	Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	Japanese oysters taken from the oiled Aber Wrach in 1979 had reached a steady state with respect to environmental exposure to weathered oil; they were able to reach background levels during a 96-day depuration period (in Maine).	Page <i>et al.</i> (1987)
Variety of shores	Brittany	Light Arabian oil/mousse from the <i>Amoco Cadiz</i> spill, 1978	Delayed effects: declines in populations of clams <i>Tellina</i> and nematodes reported 1 year after spill at St. Eflam and Bay of Morlaix, respectively.	Conan (1982)
Sediments in experimental trays	Sequim Bay, Washington	Experimental application of Prudhoe Bay crude, 1976	Initial concentrations of oil in sediments upon field emplacement were up to 5000–6000 ppm; no substantial inhibition of recruitment by benthic organisms.	Anderson <i>et al.</i> (1978)
Salt marsh	Buzzards Bay, Massachusetts	No. 2 fuel oil from the <i>Florida</i> spill, 1969	Recovery of fiddler crab population was correlated with the disappearance of naphthalene in sediments; not complete after 7 years.	Krebs and Burns (1978)
Stonework jetty	Buzzards Bay, Massachusetts	No. 2 fuel oil from the <i>Florida</i> spill, 1969	Reasonably functioning population of oyster drill <i>Urosalpinx cinerea</i> re-established at Wild Harbour by 1975, but with greater year-to-year variation in genetic structure than at reference site.	Cole (1978)
Salt marsh	Steart, Somerset, England	Experimental applications of Forties crude, 1979	No detectable retention of experimental oil in sediment samples of May 1981, but flora did not recover to control levels during 1981 growing season.	Baker <i>et al.</i> (1984)

TABLE 7 Continued

Shore Type	Location	Oil	Observations on Recovery	Reference
Salt marsh	Stear, Somerset, England	Experimental applications of Forties crude, Flotta residue and mousse, 1981	Recovery of all treated plots started during 1982, but <i>Spartina</i> density remained low in the Forties crude plot throughout 1982.	Baker <i>et al.</i> (1984)
Intertidal sea grass beds	Angle Bay, Milford Haven, Wales	Experimental applications of Nigerian crude	No visual effects on sea-grass following tidal removal of oil, but no increase in cover during growing season following treatment (compared with increase of cover in control).	Howard <i>et al.</i> (1989)

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APPENDIX A

COLD WATER ECOSYSTEMS

Marine cold water ecosystems are characterised by high seasonal temperature fluctuations relative to tropical and sub-tropical waters. As a result, the diversity of the fauna and flora is generally lower than at lower latitudes. Because of the better mixing of the water layers in cold water areas, productivity is still relatively high. Fauna of cold water ecosystems also tend to adopt reproductive strategies that involve a higher degree of brood protection and thus are believed to recover more slowly from major ecological damage.

PHYSICAL CONDITIONS

Cold water ecosystems, in the context of the marine biospheres, include those marine habitats found in temperate, boreal/antiboreal, subpolar and polar seas. Circumglobal cold water habitats also exist in the deep sea; however, since this review is primarily concerned with the natural recovery of coastal littoral and sublittoral environments, discussion of the deep sea environment is excluded.

The extent of the cold water habitats in the world's oceans is shown in Figure 8. In the southern hemisphere, the boundaries between the regions are relatively uncomplicated, with the transition between the polar/subpolar, antiboreal and temperate zones following latitudinal parallels across the oceans in the southern hemisphere. The boundaries between the temperate and tropical zones are displaced south on the western boundaries of the Indian and Atlantic Oceans and north on the eastern boundaries as a result of the interaction between the continental masses of South America and Africa and the main global oceanic currents (Bogdanov, 1963).

In the northern hemisphere, the boundaries between the temperate, boreal and polar seas are more complicated, since there is no direct latitudinal interconnection between the oceans. The displacement of the boundaries is most marked in the northern Atlantic Ocean, where the Gulf Stream pushes the boreal/subpolar boundary 30° further north on the eastern margin of the ocean. A consequence of the greater preponderance of land masses in the northern hemisphere and the greater displacement of zonal boundaries is that there is a much greater cold water coastline in the north than the south. For example, antiboreal coastline is represented only by the southern tip of South America and a few southern ocean islands (see Figure 8).

Cold water ecosystems range in annual mean temperature from around 18°C in the temperate zones to 5°C at the edge of the cool or boreal/antiboreal zones. At higher latitudes (polar and subpolar), surface temperatures are below 5°C. Probably of more ecological significance is the difference in annual temperature range between the different zones. In tropical regions, surface water temperatures show an annual variation of no more than 2°C

(Ekman, 1967), whereas in temperate to subpolar waters this may reach up to 10°C (see table below). Temperature changes are seasonal in cold water ecosystems and are thus important in controlling cyclical biological events such as reproduction. As a result of thermally induced mixing of water layers, seasonal temperature changes are an important factor in enhanced productivity in these regions (Koblentz-Mishke *et al.*, 1970).

In addition, temperate to subpolar regions correspond to a band of greater atmospheric turbulence and experience many storms, especially during winter, with gales and heavy precipitation (Gross, 1987). This turbulence also aids water mixing and hence nutrient dispersion, resulting in a greater likelihood of high-energy shores on coastlines in this region.

Mean Surface Temperatures in the Coldest and Warmest Months and the Annual Mean at the Boundaries of the Atlantic Boreal Region

	Temperature, °C		
	February	August	Annual Mean
Murman coast, Kola peninsula	1	9-10	4
Northern Iceland	0-1	8-10	3-4
Bear Island (between Spitzbergen and Norway)	0-1	5	2-3
Southern tip of Greenland	1	5	3
English Channel, southwestern entrance	9	17	12-13

(from Ekman, 1967)

FAUNA AND FLORA

The cold water environment embraces a range of temperature regimes and other climatic factors that place stress on the plant and animal communities. These stresses are manifested principally in a reduction of coastal species diversity that broadly forms a gradient from low to high latitudes (Sanders, 1968). Another consequence of the more stressful conditions is greater instability in the communities, which can vary both in species composition and abundance from year to year, relying heavily on successful recruitment of short-lived organisms each season. Such reproductive strategies theoretically favour rapid recovery after environmental impact. However, reproductive strategies, particularly of the fauna, also relate to the severity of the environment. Marine fauna may reproduce either by viviparity (the bearing of live young), direct development (directly from egg to miniature adult), or by larviparity (the egg develops into a larval form that spends some time in the water column before settling and metamorphosing into a miniature adult). In the latter case the larvae may be planktotrophic, in which case they feed on other organisms in the plankton, or lecithotrophic where they are nourished by a yolk supplied by the parent.

Planktotrophic larvae hatch from small eggs, since they do not carry food reserves, whereas other reproductive strategies are characterised by large egg production to accommodate nourishment for the developing embryos (Thorson, 1957). Because the energy available to a parent for egg production is limited, the larger the egg the smaller is

the number of eggs produced. Thus, the potential for a population of non-pelagic breeders to recover quickly from a mass mortality is considerably less than for one producing large numbers of planktotrophic larvae.

In the higher latitudes, where the summers are short and the plankton production curtailed, there is a tendency for fewer animals to reproduce with planktotrophic larvae and a preponderance of species with viviparous or direct development (Thorson, 1950) or a brooding habit (Wells and Percy, 1985). This is illustrated for marine snails in Figure A1.

The implication is that communities from higher latitudes (subpolar and polar) may recover more slowly from environmental damage than those from farther south, where planktotrophic reproductive strategies predominate (Dunbar, 1968; Clarke, 1983).

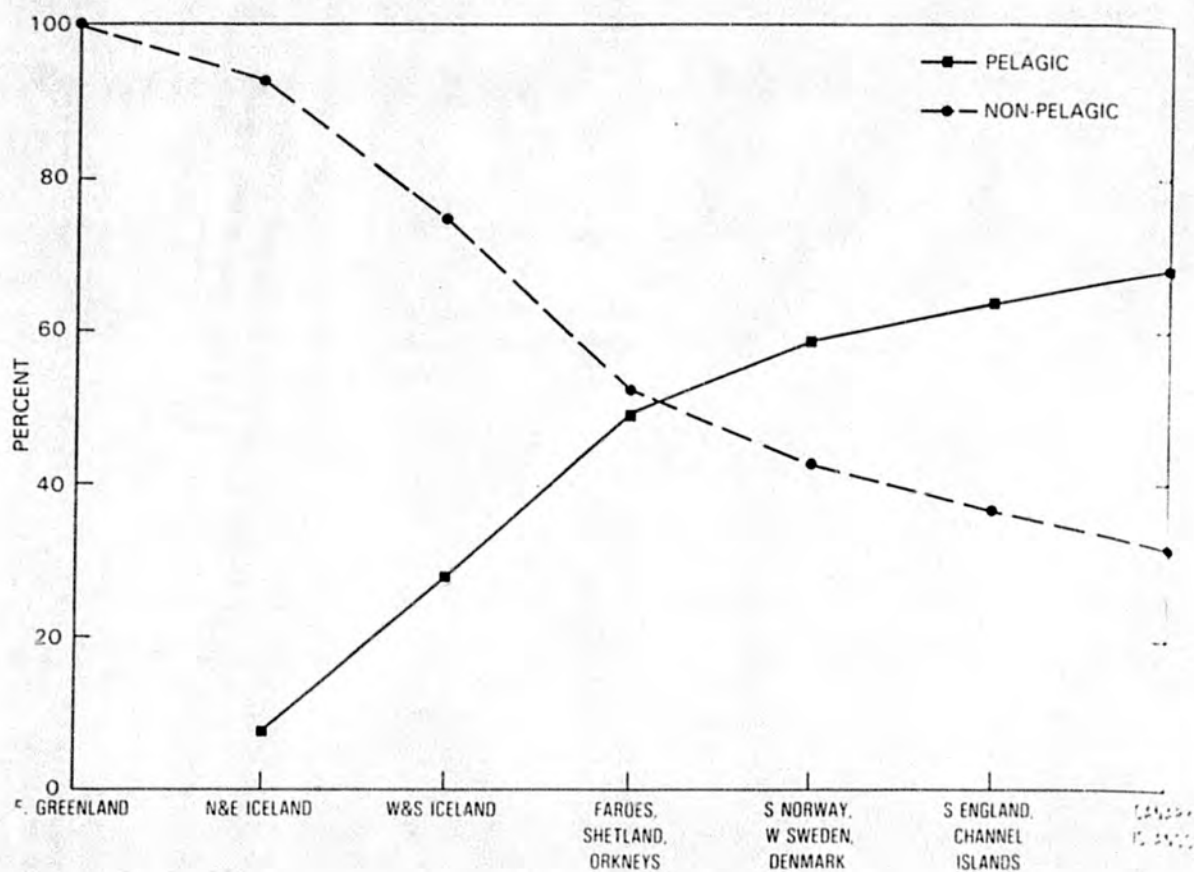


Figure A1: The relations between a pelagic/non-pelagic larval development in prosobranchs throughout the North Atlantic (Thorson, 1950).

APPENDIX B

PHYSICAL AND CHEMICAL BEHAVIOUR OF SPILLED OIL

BEHAVIOUR AT SEA

The marine environment may be divided into the open water or pelagic division and the seabed or benthic division. The benthic division extends from the top of the shore to the deepest part of the ocean. These divisions form various ecological zones (Figure B1) and broadly follow a scheme first proposed by Hedgpeth (1957).

In oceanic waters, impact from oil spills is likely to be minimal and confined more or less to the surface and near-surface water layers. The greatest impact is usually in coastal waters and on shores (littoral zones).

The shoreline, where land, air and sea meet, is the most dynamic part of the ocean (Gross, 1987). Its nature is determined by tides, winds, waves. The most obvious of the factors are waves which, together with offshore currents, are most influential in determining the type of intertidal substratum. Where the shore is sheltered from rigorous wave action (so-called low-energy shores), sedimentary beaches will form. These may range from highly sheltered or estuarine mud flats, through sand beaches, to gravel or boulder shores where wave and current action is strong enough to wash fine particles away faster than they are brought in. Rocky shores exist where the effect of waves on the coastline is mainly erosive, wearing down the softer materials and carrying them away, leaving the hardest rocks exposed. Rocky shores are biologically zoned, with the zones varying in extent depending upon the slope of the rock surfaces, the tidal range, and exposure to wave action. Thus for a given tidal range and shore gradient, the range of the littoral zone increases with increasing wave exposure (see Figure B2).

When crude oil and petroleum products are released at sea, they are subject immediately to a series of complex interactions of physical, chemical and biological processes (Koons, 1987). These processes are collectively called 'weathering' and include

- Spreading
- Evaporation
- Sinking
- Dissolution
- Natural dispersion into the water column
- Emulsification
- Biodegradation and photolysis

The time-frame following an oil spill over which the above processes occur is illustrated in Figure B3.

The significance of these natural processes in determining the fate of spilled oil is determined by a number of factors, such as the type of oil spilled and the oceanographic and meteorological conditions. A brief discussion of the above processes follows.

Spreading

Spilled oil initially spreads over the sea surface to form a relatively thin slick. Under the influence of 'weathering' and winds, thicker layers of oil/mousse may be formed.

Under the influence of gravity and the difference in density between oil and water, the spilled oil will spread over the surface of the sea. Amongst the mathematical models which describe this process, the best known are those of Blokner (1964) and Fay (1969).

Several models are available to predict the movement or drift of the surface slick under the influence of winds, surface currents, and waves. There is a tendency, with time, for the oil slick to become non-homogeneous in thickness, and to form lenses of thicker portions of oil which align themselves along the direction of the wind to form 'windrows'. The formation of thicker lenses of oil becomes more significant as the viscosity of the oil increases due to 'weathering'. Hollinger and Mennella (1973) have reported that as much as 90 percent of the oil in the slick (after evaporation) may be associated with these thick patches, although the major area of a slick is composed of a relatively thin sheen.

Observations made at the Ixtoc 1 oil well blowout (Atwood *et al.*, 1980) indicated that near the blowout, the oil slick thickness ranged from 1 to 4 mm. However, at a more distant location, long lines of thicker material were observed surrounded by thin films of oil. At times, the winds rolled the portions of the slick upon itself, and rafts of agglomerated material up to 1 m thick were seen 5 to 15 nautical miles from the spill site.

Evaporation

Most of the toxic components in crude oil rapidly evaporate after spillage, and disperse into the atmosphere to background levels. Evaporation is a major process for the removal of oil from the sea surface for lighter crudes.

When oil is released, the volatile components rapidly evaporate. For example, estimates from major incidents such as the Ekofisk Bravo, Amoco Cadiz, and Ixtoc 1 indicated that 30 to 50 percent of the spilled oil evaporated within the first few hours or days. This process is especially dominant in the initial phase following a spill and is a major process that removes oil from the sea surface—particularly for light crudes.

The rate of evaporation is dependent upon

- Spreading (the increase in surface area of the oil will facilitate evaporation)
- Temperature

- Wind speed
- Sea state conditions
- Oil composition

Spills of light petroleum products such as liquefied petroleum gas (LPG) and gasoline will evaporate very quickly, leaving virtually no residual surface slick.

The volatile components in crude oils which evaporate include the toxic hydrocarbons benzene and the mono-nuclear aromatics. After evaporation, these organics disperse into the atmosphere and are rapidly diluted to 'background' levels. Payne *et al.* (1980) found that air samples taken immediately above the surface slick of freshly spilled oil at the Ixtoc 1 oil spill had concentrations of benzene below the level for detection (1 ppb) by selected ion monitoring.

For spills of relatively non-volatile materials such as heavy fuel oils and Bunker C, the evaporation losses from the slick would be much lower. Studies following the *Potomac* spill of Bunker C oil in Melville Bay, Greenland (Petersen, 1978), attributed additional factors such as light winds, low water temperatures, thick oil slicks, and the oil composition to the low evaporation rates experienced.

Sinking

Most crude oils have little tendency to sink to the seabed even after extensive weathering and associated density increases. Oil concentrations in the water column measured below the surface slicks at sea trials and oil spill incidents have been very low. Similarly, samples of the seabed taken at offshore oil spill sites have been only lightly oiled. Some oil may reach the seabed associated with particulates. This process is unlikely to be significant for spills offshore unless the seawater is highly turbid. Spills of very dense oils (e.g., heavy fuel oil) may weather to form slicks of sufficient density to sink to the seabed.

Wilson *et al.* (1985) conclude that most crude oils have little tendency to sink to the seabed even after extensive weathering and the density increases associated with emulsion formation. They attribute reports of oil sinking to the ability of heavy oil slicks to adopt a position just below the sea surface and so become undetectable by remote sensing systems such as IR.

Sea trials carried out with Ekofisk crude oil (Cormack *et al.*, 1978) showed a rapid decrease in oil concentration, falling to 0.02 to 0.08 ppm at 10 to 15 m below the oil slick. Measurements taken approximately 50 hr after the well had been capped indicated oil concentrations as low as 0.055 to 0.118 ppm at a 1-m depth below oil sheens (Cormack and Nicholls, 1978).

Maximum subsurface concentrations of oil measured at major spills are 0.30 ppm for Ekofisk Bravo (Grahl-Nielsen, 1978), 0.35 ppm for *Amoco Cadiz* (Calder *et al.*, 1978), and 0.45 ppm for *Argo Merchant* (Grose and Mattson, 1977).

At the Ixtoc 1 oil well blowout, the hydrocarbons were released subsea which resulted in relatively high concentrations (10.6 ppm) of oil droplets measured in the top 20 m of the water column near the spill site (Fiest and Boehm, 1980). Boehm and Fiest (1980) concluded that only 1 to 3 percent of the oil spilled partitioned into the sediments. However, the area experienced a hurricane before the samples were taken. This might have significantly affected the contamination levels of the sediments.

The sediments sampled from the seabed in the area of the Ekofisk Bravo blowout, had relatively low concentrations of oil immediately after the blowout and fell to background levels 4 to 6 weeks after the well had been capped (Johnson *et al.*, 1978). Studies of the biological populations in the sediments (Addy *et al.*, 1978) were not able to attribute any specific changes to the blowout.

Significant levels of oil contamination of sediments are most likely to occur in the nearshore environments, where substantial quantities of sediments are suspended in the water column by the wave energy (see later section entitled Behaviour Near Shores).

Petersen (1978) studied the spill of Bunker C heavy fuel oil in Melville Bay, Greenland, when a combination of low water temperatures (3 to 4°C), light winds (0 to 7 knots) and calm seas resulted in relatively slow evaporation, biodegradation and dispersion rates. However, because of the special conditions described above, this can be viewed as an exceptional situation. Pancakes of spongy material ranging from 8 to 15 cm in diameter arranged in windrows on the sea surface were observed 15 days after the spill. It was estimated that most of the residues eventually sank in less than 50 days.

Dissolution

Less than 1 percent of spilled oil is likely to be dissolved into the seawater. Although the water-soluble constituents of oils are relatively toxic, they are rapidly diluted to very low concentrations in the water column.

The components of oil which dissolve in the seawater are the volatile, low molecular weight compounds which are relatively toxic. However, on physico-chemical grounds it is expected that the evaporation rates of such compounds would be two orders of magnitude greater than rates of solution (Cormack, 1983). Furthermore, a substantial proportion of these dissolved hydrocarbons are likely to be evaporated from the water column.

Because of their toxicity, the dissolved components pose a potential threat to marine life. However, this toxic effect is short-lived because the soluble components are quickly dissolved from the fresh oil and rapidly diluted in the water column to very low concentrations. Measured concentrations of dissolved hydrocarbons underneath slicks were less than 0.1 ppm (McAuliffe, 1986). Payne *et al.* (1980) measured up to 0.1 ppm of

benzene, toluenes, xylenes and other low molecular weight aliphatic and aromatic hydrocarbons in seawater samples taken immediately beneath the surface slick near to the Ixtoc 1 oil well blowout.

It has been estimated (Mackay and McAuliffe, 1989) that less than 1 percent of the crude oil spilled would be likely to dissolve into the seawater.

Natural Dispersion Into Water Column

Natural dispersion is generally recognised to be a major process for the removal of oil from a surface slick by the formation of small droplets. The process is favoured by high wave energy conditions and for low-viscosity oils.

Natural dispersion is the process whereby small oil droplets (0.01 to 0.1 mm) are generated from an oil slick by wave energy. Because of their small size, the droplets disperse speedily into the body of water, resulting in ever-decreasing concentrations.

Natural dispersion is generally recognised to be a major process for the removal of oil from the sea surface. This is particularly the case for low-viscosity, lighter oils which do not form highly viscous weathered materials. Studies carried out following the Ekofisk Bravo blowout (Cormack, 1983) indicated that only about 1 percent of the initial quantity of oil spilled would remain as a surface slick after about 80 hours. Sea trials with the Ekofisk crude oil indicated that even in moderate sea conditions, natural dispersion represented a major process which contributed to the complete removal of oil from the sea surface.

The rate of dispersion of oil is enhanced by high wave energy conditions and is inhibited with increased viscosity of the oil slick. Evaporation of the volatile components leads to an increase in viscosity of the remaining slick, but the most significant increases can result from the formation of water-in-oil emulsions (discussed below). Slicks of highly viscous oils/emulsions are relatively persistent due to their cohesiveness (Mackay and McAuliffe, 1989). Floating slicks of viscous emulsions are slowly broken up into smaller rafts or pancakes of material, then finally form tarballs. When this material reaches the nearshore, where sediments are suspended in the water column, the sediments can become enmeshed into the residual oil to form asphaltic deposits or pavements. Floating tarballs on the sea surface are relatively innocuous to marine life, but may persist for many months or years.

Emulsification

The formation of water-in-oil emulsions (mousses), which commonly occurs following marine oil spills, can have a very significant effect on the fate and behaviour of spilled oil. Some crude oils rapidly form stable emulsions of very high viscosity and form slicks which are relatively persistent.

The formation of water-in-oil emulsions (mousses) can have a significant effect on the fate and behaviour of spilled oil. Some crude oils and fuel oils have been shown to form very stable emulsions that contain 20 to 80 percent seawater. These emulsions have densities approaching that of seawater and viscosities exceeding 100,000 cP (EEC, 1986). Slicks of highly viscous material are relatively persistent (*i.e.*, resistant to natural dispersion).

The key compositional factors in the oil which favour the formation of stable/viscous emulsion are not known, but are believed to include asphaltenes, waxes, natural surfactants and surfactants formed by photolysis. Emulsification is also enhanced by low temperatures and by high-energy conditions.

The formation of mousse is a very common feature of marine oil spills. The emulsification process leads to an increase in the quantity of material in the slick, its density, its viscosity and, hence, its persistence on the sea surface. Light refined petroleum products such as gasoline usually do not form water-in-oil emulsions.

Biodegradation and Photolysis

Biodegradation is regarded as the ultimate fate of much of the dissolved and dispersed oil, but the process generally has a long time scale. The rate is controlled by oxygen and nutrient availability, temperature, chemical composition, and the surface area of the oil. Photolytic oxidation of some oil components occurs under the action of ultraviolet radiation (in sunlight). The oxidation products from both biodegradation and photolysis may be relatively toxic, but are biodegradable, water-soluble and rapidly dilute to very low concentrations in the sea.

Naturally occurring populations of bacteria, yeast and fungi which are present in seawater (and in other environments) are capable of degrading petroleum hydrocarbons to oxidation products. Biodegradation is regarded as the ultimate fate of much of the dissolved and dispersed oil, but the process takes place over a long time scale. The rate of biodegradation is controlled by temperature, oil composition, surface/volume ratio of the oil, and the supply of oxygen and of nutrients such as nitrogen and phosphorus. Bacteria preferentially attack the low molecular weight components in the oils and the normal paraffins.

Water samples taken at the mouth of Aber Wrach following the *Amoco Cadiz* spill indicate a large reduction in nC-17/pristane and nC-18/phytane ratios and an increase in the content of branched, cyclic and aromatic hydrocarbons compared with samples taken near the spill site (Calder and Boehm, 1981). From this, the authors conclude that biodegradation was occurring at a faster rate than evaporation or dissolution.

The biodegradation of the mousse formed from the Ixtoc-1 blowout was found to be extremely slow (Atlas *et al.*, 1980), and the supply of nutrients was suggested as the limiting factor. Higher rates of biodegradation of mousses and of stranded tarballs when they are associated with decaying plant material have been observed (Boehm and Fiest,

1980; Blumer *et al.*, 1973), presumably due to nutrients. The biodegradation of oil in sediments is discussed later in the report.

Under the action of ultraviolet radiation (in sunlight) and the presence of air, some components present in oil are oxidised by photolysis. These oxidation products include phenolic and acidic compounds that are water-soluble and biodegradable. The oxidation products derived from photolytical reactions of spilled oils are relatively soluble. However, their rates of generation at the surface of spilled oil are slow because they are controlled by diffusion. Consequently, if these products are leached from the surface of the oil and enter the water column, they are rapidly diluted. Although the effects on marine life due to the formation of these oxidation products have not been quantitatively assessed, they are unlikely to have significant ecological impact.

BEHAVIOUR IN ICE

Oil may be entrained within a developing ice field under freezing conditions. This process would significantly reduce or even stop evaporation, dissolution, biodegradation and dispersion of the oil.

From a series of field experiments, Wilson and Mackay (1986) concluded that significant quantities of oil may be entrained within a developing ice field under freezing conditions. The extent of oil incorporation was enhanced by

- A high oil density and/or viscosity occurring naturally or induced by weathering
- The presence of sufficient turbulence to disperse the surface oil and to induce mixing within the ice field
- The formation of emulsions of seawater and/or ice in oil
- The formation of small oil droplets
- The formation of coalesced ice particles measuring about 5 mm in diameter

The authors also concluded that the densest oils would be released relatively slowly from a frozen pancake during thawing. Once the oil begins to collect on the surface of the ice, solar radiation will tend to hasten the thawing process.

From a series of experiments in flow-through tanks, Payne *et al.* (1987) observed that extremely rapid formation of stable water-in-oil emulsions occurred under ice-forming conditions. Emulsions of Prudhoe Bay crude oil were formed within four hours of initiating waves in the presence of grease ice and breaking or rotting ice floes. They attributed this rapid emulsion formation to the low water temperatures and to the micro-scale turbulence created by the grinding of the grease ice crystals, which injected small water droplets into the viscous oil. On thawing, these emulsions were sufficiently dense to cause them to reside immediately below the grease ice. With continued agitation and melting, the emulsions eventually surfaced into patches of open water between the individual ice floes.

When oil is trapped into ice, weathering processes such as evaporation, dissolution, biodegradation and dispersion are significantly retarded or even stopped. Hence when released after thawing, the oil will be relatively 'fresh'.

In addition to being rapidly formed, emulsions formed in the presence of developing ice have significantly higher viscosities than those formed under ice-free conditions.

BEHAVIOUR NEAR SHORES

The coastline exposure and geomorphology are very important factors which influence the retention and dispersal of oil in the nearshore areas. The churning action of waves in shallow waters may result in the oil being incorporated into sediments. Beached oil may be washed off and may also become incorporated into subtidal sediments. Alternatively, the oil on the beach may be refloated and transported to impact other stretches of the coastline, or dispersed into the water column as fine droplets. Oiled sediments on beaches could be buried under fresh deposits of sand. However, oil transported from beaches is usually weathered and less toxic than fresh oil. High-energy rocky shores tend not to accumulate oil and, if impacted, are rapidly cleaned by wave action.

Because of the turbulence in shallow inshore waters and the churning action of waves, the relatively high sediment burden of these waters can result in oil being incorporated into the bottom sediments to a greater extent than in the offshore environment.

The oil stranded on the intertidal coastal areas may be partially removed by subsequent tides and transported to unimpacted stretches of the coastline. During the first two weeks following the *Amoco Cadiz* oil spill, a total of 72 km of coastline was heavily impacted (Hayes *et al.*, 1979). One month after the incident, 84 percent of the stranded oil was estimated to have been naturally removed from the shoreline. But the impacted area had increased to 213 km of lightly oiled and 107 km of heavily oiled beaches.

Hayes *et al.* (1979) also report that the geomorphology in the coastal zone was very important in the dispersal and accumulation of oil once it came onshore. Exposed rocky coastlines did not accumulate significant quantities of oil. Mousse and oil stranded on fine-grained sandy beaches or sediments did not usually penetrate far below the surface.

Sandy beaches may undergo cycles of erosion and deposition in response to changing wave conditions. Hence, high-energy beaches may rapidly self-clean or, alternatively, the oiled sediments may become buried under fresh deposits of sand, dependent upon the phase of the beach cycle.

Local entrapment of oil was found to occur between rock crevasses, in marsh pools and in scour pits around boulders. Penetration of oil into coarse-grained sandy beaches, mixed sand and gravel beaches, and gravel beaches may occur rapidly.

Oiled sediments washed from the beaches can be a major contributor to oiling of subtidal sediments. This is not an important process for high-energy, rocky coastlines.

Harper *et al.* (1985) studied the retention and residence times of oil in low-wave-exposure, tidal flat environments. Their main conclusions were that

- Retention of oil in the sediments was proportional to the loading thickness, up to a limit beyond which the retention increased very little. This limiting thickness for oil loading was thought to be a function of the sediment size.
- The retention was proportional to the sediment emergence time. Intertidal sediments which are exposed longer have greater oil retention times.
- The retention was inversely proportional to the mud content of the sediments. Even small amounts of mud may significantly reduce oil retention in sediments.
- Sediment size and composition were thought to be the most important factors which influence oil retention.

Mechanical removal of bulk oil from beaches is beneficial (1) by reducing a potential source of oiling of the subtidal sediments and other stretches of the coastline and (2) by enhancing the self-cleaning of intertidal sediments.

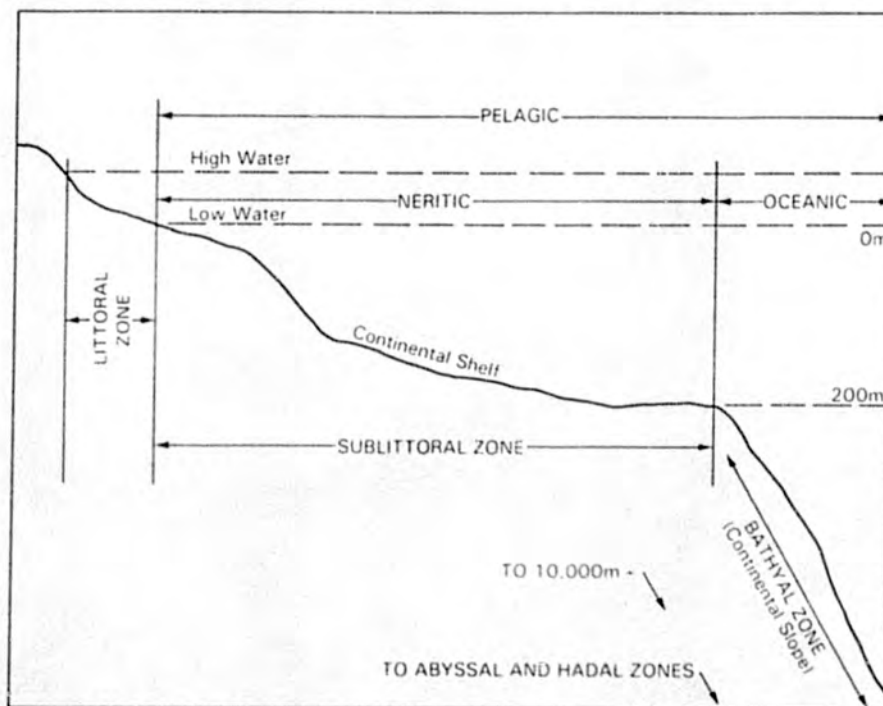


Figure B1: Divisions of the marine environment (modified after Hedgpeth, 1957).

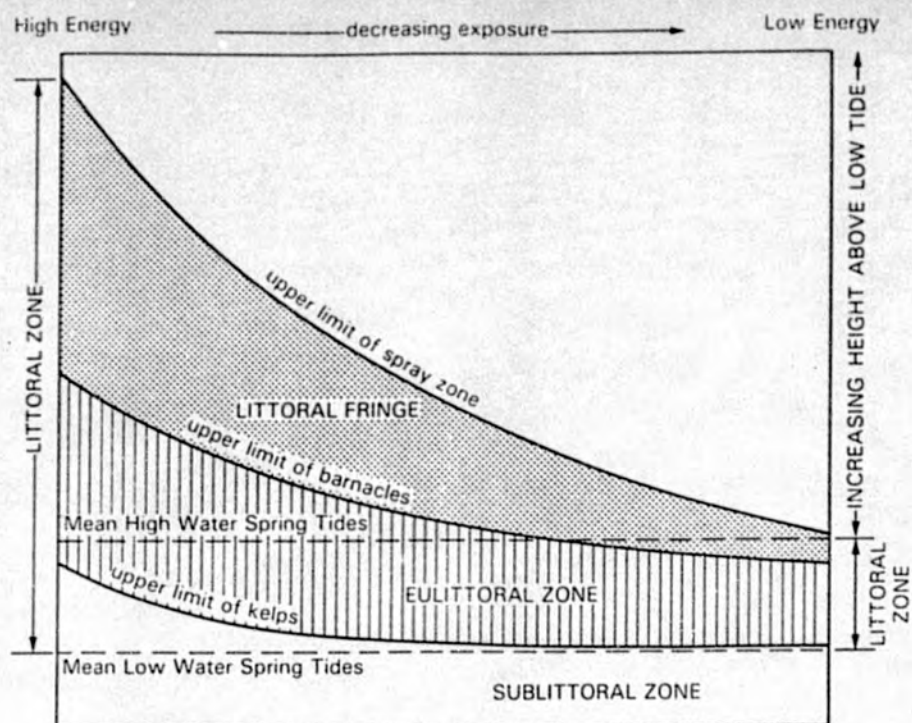
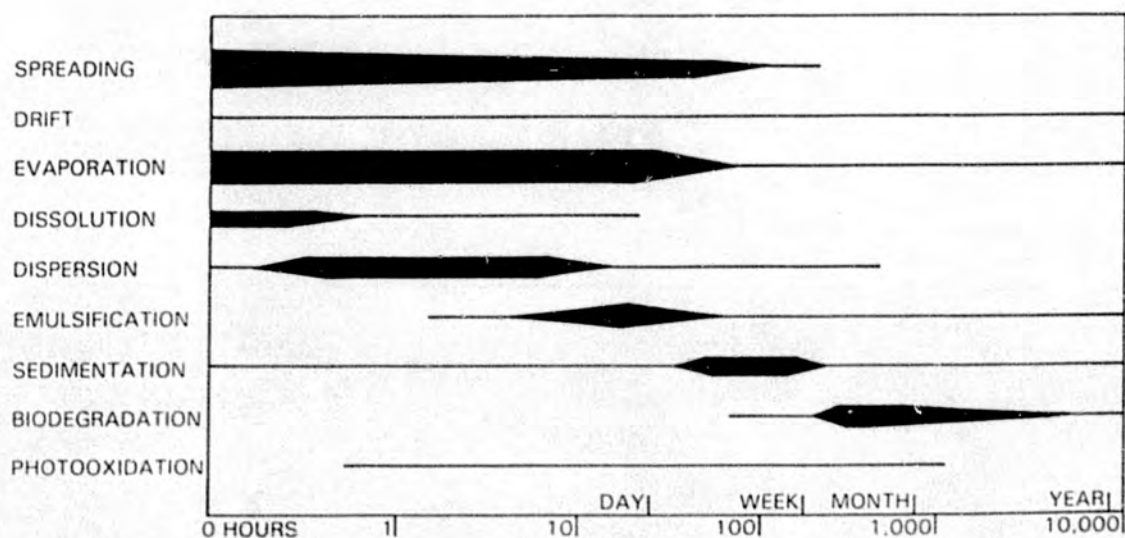


Figure B2: Effect of exposure on the width of the littoral zone of a rocky shore (modified after Lewis, 1964).



LINE LENGTH - probable time span of any process.

LINE WIDTH - relative magnitude of the process both through time and in relation to other contemporary processes.

Figure B3: Time span and relative magnitude of processes acting on spilled oil (modified after Whittle *et al.*, 1982).

APPENDIX C

EFFECTS OF OIL ON BIRDS

The most serious effect of oil is on the bird's plumage. Oil mats the feathers and destroys their water-repellant properties. For aquatic birds, this results in water displacing the air normally trapped under the plumage. This air layer provides buoyancy and thermal insulation. Birds with a water-logged plumage may sink and drown, but will certainly suffer rapid loss of body heat; fat reserves are used to counter this, but within a short time these are exhausted and the birds succumb to hypothermia, pneumonia, or related diseases. It may be anticipated that birds are more likely to die after oiling in cold climates (Brown, 1982) or after prolonged stormy weather has prevented feeding and energy reserves are low (NERC, 1971).

Lightly-oiled birds are able to clean themselves by preening within about 2 weeks (Birkhead *et al.*, 1973), but in doing so swallow oil. Depending on the age and toxic properties of the oil, this may cause gastric disorders (Croxall, 1977) and may reduce egg-laying or decrease the fertility of eggs that are laid (Grau *et al.*, 1977). While these factors may result in additional deaths or depress reproduction for a time, they are insignificant compared with the direct mortality from oiling.

If oil is transferred from the plumage to incubating eggs, the developing embryo may be killed and breeding success reduced (Brown, 1982), although there is no evidence that this happens on a large or widespread scale.

Birds at Risk

The casualties of oil pollution (*e.g.*, bilge water, dirty ballast water, *etc.*, as well as oil spills) are overwhelmingly aquatic birds, though in exceptional circumstances shore birds or even land birds may be affected. The following birds are most at risk.

Alcids (auks)

These include murre, guillemots, razorbills, puffins, *etc.* They are weak fliers and spend virtually all their time on the surface of the sea, returning to land only for breeding. They hunt their food (small fish) under water and are very gregarious at all times of the year. Because of their habits, auks are more likely than most birds to encounter oil slicks and, since they dive rather than fly up when disturbed, may surface through the oil slick and become coated with oil. Because they occur in large, dense flocks on the water, casualties from an oil spill are likely to be high.

Diving Sea Ducks

Many species of sea duck disperse to land or fresh water for breeding, but occur in very large flocks in coastal waters during the fall and winter. Some species dive for their food in a similar manner to auks and are vulnerable to oil slicks in the same way. But for all species, casualties may be very high if oil impacts winter flocks in coastal waters.

Grebes and Loons

These, like auks, are divers and weak fliers. They breed in fresh waters but spend the winter in ice-free coastal waters. They are likely to become oiled if they encounter an oil slick, but since they occur in only small groups, casualties are usually small. However, because the world population of these birds is small, even low casualties may be significant.

Pelican, Gannet, Tern

These birds dive from the air into the sea to catch fish. If, as sometimes happens, they dive through an oil slick, they become coated with oil. Pelican and gannet casualties have been reported, though not in large numbers. Terns appear to avoid this hazard.

Other Birds

Almost any seabird or shore bird may encounter floating or stranded oil and suffer some oiling of the plumage, the extent of which is usually slight, and casualties are small.

BIOGRAPHICAL SKETCHES OF THE AUTHORS

DR. JENIFER M. BAKER

Dr. Baker is a biological consultant specialising in environmental impact assessment and oil spill response. Her doctoral studies at the University of Wales involved research on the effects of oil on and cleaning methods for salt marshes, and she has subsequently worked on oil pollution problems in many parts of the world. She was formerly Research Director of the UK Field Studies Council, and is presently a fellow of the Institute of Biology and of the Institute of Petroleum. Dr. Baker has published numerous papers in the scientific literature on the subject of the recovery of impacted shoreline ecosystems.

DR. ROBERT B. CLARK

Dr. Clark is currently Professor Emeritus of Zoology at the University of Newcastle upon Tyne. He received his Ph.D. from the University of Glasgow and a D.Sc. from the University of London. He has served as Honorary Director of the Seabird Research Unit of the British Advisory Committee on Oil Pollution of the Sea (1969-75), and as Director of the Natural Environmental Research Council (NERC) Research Unit on Rocky Shore Surveillance (1980-87). Dr. Clark also worked with numerous national and international bodies, including the United Nations group of experts on the Scientific Aspects of Marine Pollution, and the Royal Commission (UK) on Environmental Pollution. His extensive publications include the textbook *Marine Pollution*. He is founder (1969) and Editor of the *Marine Pollution Bulletin*.

DR. ROWLEY H. JENKINS

Dr. Jenkins became Deputy Director, in 1986, of the Institute of Offshore Engineering at Heriot-Watt University in Edinburgh, Scotland. He had earlier served 28 years in the petrochemical and oil industry in research and environmental areas. His current focus in oil spill research includes emulsification and weathering, as well as modelling and fingerprinting by GC/MS analysis. Part of his environmental experience involved a two-year secondment to Woodside Petroleum as Environmental Coordinator for the North West Shelf Gas Project in Western Australia. In his post as Oil Spills Divisional Manager for British Petroleum (BP), Dr. Jenkins provided the BP group worldwide with a wide range of services — e.g., emergency response from the Southampton Oil Spill Response Base, equipment testing and appraisal, and oil spill response training. He was active in both CONCAWE and IPIECA as the BP representative.

DR. PAUL F. KINGSTON

Dr. Kingston obtained his doctorate from the University of London and, after a three-year post-doctoral research fellowship at the University of Newcastle upon Tyne, joined the staff at Heriot-Watt University in 1975 as lecturer in marine biology. He is currently the

Assistant Director of the Institute of Offshore Engineering. Earlier, he had acted as Consultant to the Institute on all offshore, inshore, and coastal environmental projects, and served as part-time Assistant Director with responsibility for biological studies. Dr. Kingston has had considerable experience in assessing the environmental impact of the offshore oil industry and has worked on most major North Sea developments. His research interests centre on the structure and dynamics of seabed communities. He has published extensively and currently serves as News Editor of the *Marine Pollution Bulletin*.

GLOSSARY

aerobic bacteria	Bacteria that can live only in the presence of free oxygen.
aliphatic hydrocarbons	Saturated straight-chain or branched-chain hydrocarbons.
anaerobic bacteria	Bacteria that can live in the absence of free oxygen.
antiboreal	Cool or cold-temperate regions in the southern hemisphere (see Figure 8).
aromatic hydrocarbons	Hydrocarbons containing one or more benzene rings in their molecular structure.
asphaltenes	High boiling point constituents of crude oils that are soluble in polar solvents such as benzene or methylene chloride but are not soluble in paraffin naphthas.
bacterial mat	A carpet of filamentous bacteria which can form over the surface layer of organically enriched sediments.
benthic fauna	Animals inhabiting the seabed.
benthos	Those forms of marine life that are bottom-dwelling; also, the ocean bottom itself. Certain fish that are closely associated with the benthos may be included (AGI).*
biodegradation	Breaking down of substances by bacteria.
biogenic	Originating from living matter.
biomass	The amount of living material in a particular area, stated in terms of the weight or volume of organisms per unit area or of the volume of the environment (AGI).
biota	All living organisms of an area; the flora and fauna considered as a unit (AGI).
bivalves	Molluscs having a shell in the form of two plates, <i>e.g.</i> , clams.
boreal	Cool or cold-temperate regions in the northern hemisphere (see Figure 8).

* American Geological Institute, *Glossary of Geology*, Third Edition

copepod	A subclass of <i>Crustacea</i> , generally of small size. These crustaceans are important members of the zooplankton and meiofauna.
crustaceans	A class of <i>Arthropoda</i> , mostly of aquatic habitat, which includes shrimps, prawns, barnacles, crabs, and lobsters.
depurate	To rid of contaminants, especially with relation to shellfish.
diatom	A microscopic, single-celled plant which grows in both marine and fresh water.
dispersants	Chemical mixtures containing surface-active agents which enhance the dispersal of oil in water.
ecosystem	Any area of nature which includes living organisms and non-living substances interacting to produce an exchange of materials between the living and non-living parts, <i>e.g.</i> , the sea, a pond, lake, or forest. It comprises four constituents: abiotic substances, producers, consumers, and decomposers, and is the basic functional unit in ecology.
emulsification	A colloidal suspension of one liquid in another, <i>e.g.</i> , mousse.
epifauna	Fauna living upon rather than below the surface of the seafloor (AGI).
eutrophication	Depletion of oxygen in the water column in response to an increase in nutrients and associated elevation in primary production.
fauna	A collective term denoting the animals occurring in a particular region or period.
fucoid algae	Brown seaweed belonging to the family <i>Fucaceae</i> .
gas chromatography	An analytical technique for the separation of components in a mixture on the basis of boiling point. The use of very sensitive detectors enables this form of chromatography to be applied to microgram quantities.
gasoline	A distillate of crude oil (boiling temperature less than 190°C), having a carbon number distribution between C5 and C10, that is used as a liquid fuel.
herbivore	An organism that feeds on plants.

infauna	Those aquatic animals that live within rather than on the bottom sediment (AGI).
intertidal	The benthic ocean environment between high- and low-tide water levels (see Figure B1). Syn. <i>littoral</i> .
lecithotropic	A form of larval development whereby the eggs are dispersed in the water column and contain an independent food source for the developing larvae.
lipids	Generic terms for fats, waxes, and related products in living tissues.
littoral	See <i>intertidal</i> (see Figure B1).
lysosomal	Cellular particles intermediate in size between mitochondria and microsomes and which contain hydrolytic enzymes.
macrofauna	Animals large enough to be seen with the naked eye.
meiofauna	Organisms in the size range of 0.1 to 1.0 mm that live within sediments.
metabolic	The chemical and physical changes constantly taking place in living matter.
mousse	A viscous water-in-oil emulsion which is often brown in color (also: chocolate mousse).
n-alkanes	Normal alkanes; straight-chain aliphatic hydrocarbons; paraffins.
nematodes	A phylum of unsegmented worms with an elongate rounded body pointed at both ends. Included are round worms, thread worms, and eel worms.
neritic	That portion of the seafloor lying between low-water mark and the edge of the continental shelf, at a water depth of about 180 m (see Figure B1).
oleophilic	Having a strong affinity or preference for oil.
opportunistic species	Species which are able to quickly colonise and exploit environmentally disturbed areas.
paraffins	A whole series of saturated aliphatic hydrocarbons of the general formula C_nH_{2n+2} .
pelagic	Living in the middle depth and surface of waters of the sea.

petrogenic	Derived from rocks.
petroleum hydrocarbons	Liquids that are generated through the action of time and temperature on organic matter buried below the earth's surface. They consist of saturated and unsaturated structural groups.
phenolic compounds	Compounds containing a hydroxyl function (OH ⁻) substituted on a benzene ring.
photolysis	The decomposition or dissociation of a molecule as the result of the absorption of light.
phytane	A branched-chain saturated hydrocarbon containing 20 carbon atoms.
phytoplankton	Plant members of the plankton.
plankton	Animals and plants floating in the water of seas, rivers, ponds, and lakes, as distinct from animals which are attached to, or crawl upon, the bottom; especially minute organisms and forms.
planktotrophic	A form of larval development whereby the eggs are dispersed pelagically and the larvae then spend time as temporary members of the plankton where they feed and grow before settlement.
polar compounds	Molecules in which the electrical charge distribution is dipolar (like a bar magnet); commonly used to refer to components of crude oil containing the elements N, S, and O in addition to H and C.
polychaete	A type of segmented marine worm, <i>e.g.</i> , bristle worm.
polynuclear aromatic	Aromatic hydrocarbons containing two or more benzene rings.
pristane	A branched-chain saturated hydrocarbon containing 19 carbon atoms.
recruitment	Addition by immigration or reproduction of new individuals to a population.
saturated hydrocarbon	A general term including straight-chain, branched-chain, and ring structures in which all carbon-carbon bonds are covalent. Syn. <i>alkanes</i> , <i>paraffins</i> .

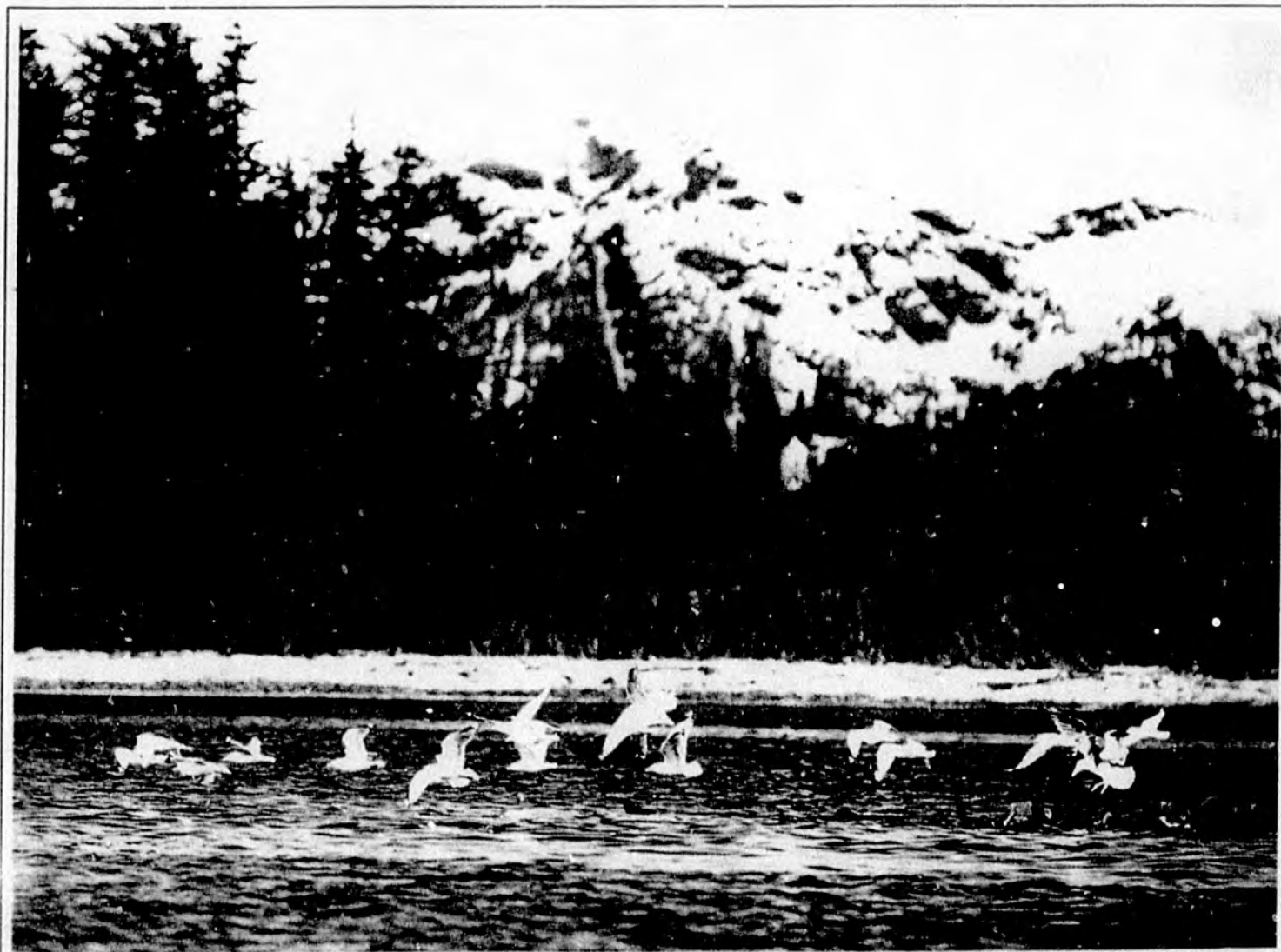
shingle	Coarse, loose, well-rounded, water-worn detritus, especially beach gravel, composed of smooth and spheroidal or flattened pebbles, cobbles, and sometimes small boulders, generally measuring 20-200 mm in diameter; it occurs typically on the high parts of a beach (AGI).
sublethal toxicity	The toxicity of a substance which is shown to cause deleterious effects in plants and animals, but not death.
substrata	Non-living materials to which a plant is attached and from which it obtains substances used in its nutrition.
subtidal	The benthic ocean environment below low tide which is always covered by water (see Figure B1). Syn. <i>sublittoral</i> .
tarballs	Water-insoluble, buoyant agglomerates formed in water from weathered crude; consist largely of the non-hydrocarbon fractions.
toxins	Poisonous substances of plant or animal origin.
zooplankton	Animal life that floats or drifts in water.

ENVIRONMENTAL RECOVERY IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

Field Observations of:

Jenifer M. Baker, Ph.D
Robert B. Clark, Ph.D
and Paul F. Kingston, Ph.D

A supplement to the authors' scientific review:
"Natural Recovery of Cold Water Marine Environments After an Oil Spill"



June 1990

INTRODUCTION

This report is based on work commissioned by Exxon as part of a programme of analyzing the ecosystem recovery process in Prince William Sound and the Gulf of Alaska following the oil spill of March 1989.

Written by three distinguished scientists, it supplements a comprehensive study they and a fourth researcher prepared on the subject of "Natural Recovery of Cold Water Marine Environments after an Oil Spill." This scientific review was presented at the 13th Arctic and Marine Oilspill Program Technical Seminar sponsored by the Canadian Government in Edmonton, Alberta, on June 6, 1990.

As a followup to this study, the scientists spent two weeks in April 1990 gathering insight into the Prince William Sound and Gulf of Alaska environment as a whole and examining plant and animal life in the area. They compared their Alaska findings to their knowledge gained from studying the recovery process from other oil spills in cold waters of the world.

The scientists, all from the United Kingdom, are:

Dr. Jenifer M. Baker, a biological consultant who works on oil-pollution problems for conservation organizations, corporations and government agencies throughout the world.

Dr. Robert B. Clark, zoology professor emeritus at the University of Newcastle upon Tyne, author of the textbook *Marine Pollution* and editor of the international journal *Marine Pollution Bulletin*.

Dr. Paul F. Kingston, a marine biologist and assistant director of the Institute of Offshore Engineering in Edinburgh, Scotland.

The following pages contain a summary of their conclusions and answers to questions they have encountered since their inspection tour in Alaska. Also, excerpts from their review of previous spills are provided in the back of this report.



Researchers closely examine a worm from a sedimentary shore. From left, Dr. Kingston, Dr. Baker, and Dr. Clark.

OVERVIEW

In April 1990, we toured Prince William Sound and the Gulf of Alaska for two weeks to obtain a perspective on the total area relative to the affected region, and to conduct field observations on the environmental impacts of the Valdez oil spill. Because the Sound and Gulf comprise an immense region with thousands of miles of coastline, most of which was not oiled by the spill, we obtained an overview with extensive low-altitude flights of the area. In addition we conducted shoreline investigations on numerous beaches, including some of the most heavily impacted areas. The map on this page indicates the broad geographical scope of our investigation.

Prior to our field investigation, we were familiar with the considerable body of scientific research focused on the biological implications of previous oil spills. Since the wreck of the tanker Torrey Canyon created a major oil spill off the southwest coast of England in 1967, the scientific community has been investigating how areas affected by an oil spill recover through natural processes. As specialists in this field

of study, we were aware of the conclusions reached through this research and therefore what one might expect to find in Alaska.

Our examination of plant and animal life in the many unoiled and previously oiled areas was designed to provide an overall perspective of environmental conditions in Prince William Sound and Gulf of Alaska. From this field analysis, we derived impressions on how the natural recovery was proceeding in Prince William Sound and the Gulf of Alaska. What follows is a brief summary of our field observations and impressions.

General findings

Our experience in Prince William Sound, one year after the oil spill, held few surprises.

Only a portion of the shoreline had been oiled, and, as with most other oil spills, the bulk of the damage had disappeared during the first year. The area has retained its natural beauty; there are abundant signs of



OVERVIEW

plant and animal life, and recovery is well under way on even the most severely impacted beaches.

Since there are few sheltered areas with extensive mudflats, which elsewhere have sometimes taken a long time to recover, the overall impact of the oil spill on the environment in Prince William Sound and Gulf of Alaska is likely to be short-lived.

The search for oil

Prince William Sound and the Gulf of Alaska are vast, mainly inaccessible areas, and the spilled oil only impacted a small portion of the total shoreline. On our visit one year after the spill, most of the shoreline of the Sound and the Gulf did not have an oily appearance. The main reasons for this generally favourable impression were: most of the shoreline was not oiled or was only slightly oiled by the spill; bulk oil had been removed by the extensive cleanup programme during the summer following the spill; the natural cleaning process has been effective, and this process includes wave action, winter storms and breakdown by bacteria.

Despite the generally favourable appearance from



Rock covered with black lichen, which can look like oil at a distance.

Most of the Prince William Sound had a generally favourable appearance.



OVERVIEW

the air, dark patches on the rocks and dark zones on the upper shore invited further investigation. On the ground, we found that many of these dark patches were formed by a black lichen, not by oil. Other noticeable dark patches were beds of algae or mussels, although some were caused by oil or oil stains.

The remaining oil

Overall rocky shores generally appeared clean from the air, and this was confirmed by ground observations. However, residues of weathered oil were present and had a varied distribution depending upon exposure to wave action and height on the shore. Most of the residual oil was found in sheltered inner bays or on upper shores.

We dug into several sedimentary shores and found oil that had penetrated below the surface. Even in the sediment bays that were heavily oiled, a variety of plants and animals were present, some of them abundant. This was consistent with recovery processes noted in other oil spills. In some areas, small oil sheens (microscopically thin films) emerged from these disturbed sediments. On some shores, there are recent deposits of fine sediment on top of oil residues, and these could help reduce any remaining surface stickiness.



Beach cleaned by strong wave action, oil stains remaining on sheltered area in the background.



Otter observed in previously oiled waters of Prince William Sound.

Sea otters

Sea otters were affected by the spill and attracted a great deal of media attention. We were therefore particularly interested to see otters in many parts of Prince William Sound and the Gulf of Alaska, including previously oiled waters. The frequency with which we saw the otters suggests that they are reasonably common throughout the Sound and Gulf.

Seals and Sea lions

Large numbers of sea lions, with at least 100 in each group, were basking on the rocks at several locations in the region. In addition, many seals were observed swimming in the open waters. Although we did not undertake a detailed study of the seals and sea lions, large numbers of them appear to exist in areas affected by the spill.

Sea birds

The dominant seabirds in the area were auks (murres) and gulls. These birds, which do not start breeding until late May or June, were primarily distributed in small feeding groups throughout Prince William Sound and the Gulf of Alaska, although large numbers were already congregating around some of the breeding colonies.

Migrant birds were only just beginning to return from their winter quarters. Small groups of mallard and other ducks were seen, in addition to a pair of swans, a group of black-bellied plover and other wading birds. Cormorants were often seen flying around

OVERVIEW



Starfish found in the tidal region of a previously oiled shore.

Prince William Sound and the Gulf of Alaska.

The most conspicuous casualties of cold-water oil spills are seabirds such as auks, which often congregate in dense flocks on the sea, making it possible for large numbers to be killed by a single oil slick. Despite this, previous research cited in the scientific review on natural recovery has shown that seabird breeding populations rebound rapidly because any losses are replaced from a large reservoir of previously non-breeding adults. Also, we would expect no further casualties since the water now appears clear of oil with only a minor sheen presence.



Fresh grass shoots sprouting from sediment containing residual oil.

Bald eagles

Bald eagles were seen perching at the top of lookout trees at regular intervals along the entire coastal area. It is not a rare bird in the area. Bald eagles obtain much of their food by foraging on the shoreline and may have been affected by oil in this way. As with other large birds of prey, bald eagles do not start breeding until the age of 3 or 4. There is therefore a substantial reserve of young adults ready to fill gaps in the breeding population as nesting territory becomes available.

Shoreline creatures

The creatures we saw most commonly on the rocky shores were barnacles, periwinkles (sea snails), mussels and limpets. They were abundant at widespread



Rock overturned in an oiled area, exposing a variety of shoreline creatures.

locations in Prince William Sound and the Gulf of Alaska, including areas which had been heavily oiled. We found egg clusters of a variety of molluscs at sites which had been oiled. Worms and shellfish were living in the sediments of the more sheltered shores, including areas which had been oiled and some of which still contained oil. Numerous worms and other creatures living in the sediment promote aeration, helping the bacterial breakdown of oil.

Sighting of numerous young barnacles on the rocks implies that environmental quality has been good enough to support these animals through the sensitive stages of the life cycle, both at sea and on shore. It is likely that shore oiling killed many barnacles, but we saw many that had survived the spill, some with oil still visible on their shells. Some young barnacles have settled next to oil crusts on the rock, indicating that

OVERVIEW



Young fucus (rockweed) growth on a previously oiled rock.



Bald eagle atop lookout tree, a common sight.

the residual oil has a very low toxicity. Periwinkles also were active on oiled rocks.

Plant life

In all marshes or upper-shore grass zones, we saw new grass shoots of normal appearance emerging from the sediment. We were particularly interested in the presence of marsh grasses at sites which were reported as heavily oiled. Many of the plants making new growth were rooted in sediments which retained visible oil residues, indicating low toxicity of the residues and the existence of a robust system of underground stems and roots.

Algae were seen throughout Prince William Sound and the Gulf of Alaska, including young rockweed plants which had established themselves after the spill. Filamentous green algae were noticeable on many shores.

We found sea or eel grass on shores which had been oiled and compared it with the grass growing on an unoiled shore. Most of the grass on all these shores looked green and healthy.

We saw numerous kelp beds with plants of normal colour along the more exposed shores of the Kenai Peninsula and the mouth of Prince William Sound.

Fish

While it was not possible to make observations of fish during our field analyses, extensive research referenced in the scientific review has shown that oil spills have little impact on fish, and, indeed, the herring fishery opened successfully while we were in the area.

CONCLUSION

Our examination of the spill area confirmed our expectations, based on knowledge gained from previous accidents, that natural recovery is proceeding in Prince William Sound and the Gulf of Alaska. We expect the recovery to continue and to be relatively rapid.

Although isolated patches of weathered oil may still be found, nearly all of the beaches in Prince William Sound and the Gulf of Alaska are of clean appearance. Some small and isolated portions of the shoreline may retain oil for several years, but our investigations of previous oil spills indicate that the long-term impact on plants and animals should be minimal.

The recovery process is well under way. Once started, if it is allowed to proceed without interruption, it will continue and be robust, as it has been following other spills throughout the world.

**What follows are answers to questions
perceived to be of general public interest.**

COMMONLY ASKED QUESTIONS

The following are responses given by the authors to questions they have been asked following their examination of Prince William Sound and the Gulf of Alaska.

Were you surprised with what you found in Alaska?

What we saw in Prince William Sound, from the point of view of biologists, confirms what the research on previous spills had told us we might expect to find. Over the past 25 years, there has been extensive research on oil spills around the world, at least 30 of them larger than the Valdez spill. That helped prepare us for what we found. What did surprise us was a smaller amount of oil on the beaches than we expected. We were impressed with how extensive the cleanup effort had been, as well as the combined effectiveness of the strong natural cleansing processes and the cleanup operation.

What is the overall impact of the spill on the ecology of Prince William Sound?

For the parts of the Sound that were affected, it was a shock. However, it was more like a rash on a human body that will heal itself, rather than a crippling or terminal disease. After the initial shock, the natural recovery process began. Animals and plants are thriving, and the environment is healing.

What is the scientific evidence on the effects of major oil spills on water quality or on Prince William Sound?



Investigators dig into the sediment to find worms and other creatures.

Indications of the good water quality in Prince William Sound are provided by biological evidence. We saw on the shoreline abundant evidence of life that has survived or has newly settled on shores that were previously heavily oiled. For example, young barnacles and seaweeds are abundant on most shores. These organisms, in their most sensitive stages, float in the water until settling. Furthermore, they are quite fussy about where they settle, and they must find suitable rock surfaces to settle upon.

Will the oil that remains in shoreline sediments pose a danger to plant and animal life?

There are abundant signs of life such as worms, shellfish and grasses thriving on many sedimentary shorelines. This indicates that sediments either do not contain toxic residues or, if they do, the level of toxicity is not high enough to affect the survival or activity of these creatures. Their presence indicates that recovery is in progress. Once started and allowed to proceed without interruption, we believe it will continue and will be robust, as it has been following other oil spills throughout the world.

Is oil a toxic compound that will persist for decades?

No, oil is not a persistent toxic compound like PCBs, mercury and many pesticides. The toxicity in oil diminishes very rapidly as it is exposed to the air and water. Most of the oil released in PWS was afloat for at least four days before it reached the shoreline, and in that time would have lost much of its toxicity. Therefore the damage it did to wildlife was not so much because of its toxicity as because of its smothering effect. It follows it is unlikely that much of the oil that remains is significantly toxic, even that trapped in shoreline pockets. We saw biological evidence for this, such as animals living in sediments with residual oil. In addition, green shoots of upper-shore grasses were sprouting normally from the oily sediment.

Are birds and wildlife threatened by oil sheens?

In our on-site inspection, we looked for sheens from the air and on heavily oiled beaches. From the air, we saw only a few sheens and they were quite small in area and very thin, as indicated by their colour. It is very unlikely, therefore, that they would be harmful to wildlife, including birds and sea otters, the animals most at risk. There is no past evidence to suggest otherwise. Animals exposed to these sheens would, in the normal course of living, groom

COMMONLY ASKED QUESTIONS

themselves.

Small sheens emerged from some sediments we disturbed on the beaches, but they were too small to have any significance for birds and other wildlife.

Has the oil entered the food chain and disrupted it?

Animals may accumulate petroleum hydrocarbons while their environment is oily, but they subsequently purge themselves in a relatively short time and return to normal levels. It is important to understand that oil is not like pesticides, mercury and other substances that cannot be metabolized, cannot be excreted, and thus build up in the flesh.

Have any species been irretrievably lost by this spill?

This is unlikely for a number of reasons. First, only portions of Prince William Sound and the Gulf of Alaska were affected. The sea is continuous and the abundant plant and animal life in the vast unaffected areas provide a reservoir of organisms to move in and replace losses created by the one-time, short-term occurrence of the oil spill. Secondly, the number of bird mortalities caused by the spill was small compared to those caused by naturally occurring phenomena such as extremely cold weather, harsh storms and old age. Finally, sea otters, which were also impacted, have a rapid reproduction rate.

Are the fish after an oil spill safe to eat?

Yes. There is ample evidence that fish avoid floating oil and are unaffected by it. Impounded fish that are exposed to fresh oil may acquire a taste of oil, but this is temporary and quickly dissipates once the fish are returned to clean waters. Even if the fish acquires an oily flavor, there is no evidence that this poses a toxicological hazard.

There are reported although unconfirmed sightings of abnormal fish and other animal life in Prince William Sound since the oil spill. Would you comment on that?

Some fish may have developed in an abnormal way if they were exposed to oil in their early stages. But it is most unlikely that these abnormalities would be passed on to the next generation. Any grossly abnormal members of the population would not survive long in the struggle for existence. On the other hand, genetic mutations, which also could

lead to abnormalities, occur naturally, and there is no evidence from previous spills that link these to oil.

How has the habitat in Prince William Sound been damaged or compromised?

The short-term impact from the spill was serious. From our observations, it is difficult to say anything definite about the long-term impacts, although recovery is well under way. Experience from other oil spills indicates that long-term impacts will be minimal.

Is there any reason to restrict normal human use of Prince William Sound for tourism, hiking, camping, hunting, fishing, kayaking, etc?

No. We were struck by the magnificent beauty of the area. We visited the most heavily oiled areas and found nothing indicating that human use should be or need be restricted because of the spill.

How can you say this "pristine and fragile" area has not been irreparably damaged by the introduction of 11 million gallons of oil?

We saw nothing to indicate the Prince William Sound environment is particularly fragile. The marine environment is a lot tougher and more resilient than most people give it credit for. Life forms in that rather harsh environment have to be hardy to survive. All the evidence suggests Prince William Sound is a robust, resilient environment well on its way to recovery.



Basking group of seals, one of many spotted on rocks throughout the region.

THE NATURAL RECOVERY PROCESS

The following are excerpts from *Natural Recovery of Cold Water Marine Environments after an Oil Spill* published by the authors and Dr. Rowley H. Jenkins, deputy director of the UK Institute of Offshore Engineering, in March 1990. These findings are based on an extensive review of research into major oil spills into cold water environments throughout the world.

BASIC CONCEPTS

- Current evidence indicates that hydrocarbons are present in all environments. They originate from both natural and human sources and serve to define background levels of petroleum hydrocarbons.
- Recovery of an ecosystem damaged by petroleum hydrocarbons begins as soon as the toxicity or other adverse property of the oil has declined to a level that is tolerable to the most robust colonizing organisms. Recovery processes can begin in the presence of residual oil.
- Recovery of an ecosystem is marked by the re-establishment of a healthy biological community in which the plants and animals of the community are functioning normally. It may not have the same composition or age structure as that which was present before the damage and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have developed in the absence of the spill.
- Ecosystems are in a constant state of flux due to natural causes. These fluctuations can be as great as, or even greater than, those caused by the impact of an oil spill.

NATURAL CLEANING

- Most of the toxic components in a fresh oil spill on the surface of the sea rapidly evaporate. After evaporation, these toxic components disperse into the atmosphere and are rapidly diluted to background levels. Most of the remaining toxic components that did not evaporate, dissolve and disperse in the water column to low concentrations.
- Generally, the higher the aromatic content of an oil, the higher the toxicity. Weathered crude is less toxic than fresh crude because most of the toxic compo-

nents have evaporated. Most of the toxic components are readily degradable.

- Oil concentrations in the water column below oil slicks are very low.
- The persistence of oil slicks on the sea surface is dependent upon the type of oil spilled and sea state conditions. Some slicks can be removed by natural processes within a few days. Other oils can form stable, highly viscous emulsions (mousses), which may persist for weeks or months in the open ocean. Eventually these slicks will form tarballs that are relatively harmless to biological systems.
- High-energy rocky shores usually do not accumulate oil, and if impacted are subjected to rapid cleaning by wave action.
- Oil does not penetrate easily into fine sediments in the intertidal zone, but can sink into shingle, gravel, and coarse sand. In some cases oil may penetrate to the water table, which forms a natural barrier to further penetration.
- On sheltered shores with high biological productivity, oil can penetrate down biological pathways, e.g., worm burrows and plant root systems. Oil may persist for many years in the sediments, especially if oxygenating biological activity (e.g., new burrow formation) is depressed.
- Physical 'removal' of oil by natural processes alone does not eliminate oil from the environment; it redistributes it. This redistribution can be beneficial - e.g., when wave action cleans the shoreline, it facilitates dispersion of the oil in the water column, and increases the surface area of the oil droplets, thereby encouraging other degradation processes. However, such redistribution may also involve sediment-bound oil being transported to the seabed.

NATURAL RECOVERY

- Diving seabirds suffer heavy mortalities from oil. However, the mortalities arising from a single oil spill are not significantly different from natural mass mortalities experienced from time to time and are significantly less than annual mortalities from fishing activities.

THE NATURAL RECOVERY PROCESS

- There is no evidence that seabird populations are declining as a result of oil spills. In fact, North Atlantic populations of most species have been increasing in recent years despite heavy annual losses from oil pollution.
- Kills of adult fish from exposure to oil are rare. The only important casualties from oil spills are rockfish and shellfish in near-shore waters, and fish in mariculture installations.
- Loss of pelagic eggs and fish larvae, when these are present at the time of an oil spill, has had no detectable impact on the fish stocks available to the fishing industry.
- Although the toxic components of petroleum hydrocarbons kill planktonic organisms, there is no evidence that these effects have any ecological significance in open waters. In closed waters, effects may persist for several months.
- Estimates of recovery times vary depending upon the environment. Past experience has shown that exposed, rocky shores usually recover in 2 to 3 years. Other shorelines show substantial recovery in 1 to 5 years with the exception of sheltered, highly productive shores (e.g., salt marshes), which may take 10 years or more to recover.
- Subtidal sand and mud systems recover in recognizable successions. Usually, recovery times are 1 to 5 years, but they can be 10 years or longer in exceptional cases.
- The early colonizers, once the physical and toxic effects of the oil ameliorate, play an active role in the breakdown of the remaining hydrocarbons.
- Removal of oil using drastic cleaning methods, beyond initial bulk oil removal, can actually delay recovery because the cleanup also removes living organisms and damages the habitat.

BIOGRAPHICAL SKETCHES OF THE AUTHORS

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Dr. Baker is a biological consultant who conducts research on oil-pollution problems for conservation organizations, corporations, and government and United Nations agencies throughout the world. She is the former research director of the UK Field Studies Council, an independent environmental education and research organization. Her doctoral studies at the University of Wales involved research into the effects of oil and cleaning methods for salt marshes, and she later served as a staff member in the botany department of the University College, Swansea. She recently helped assess potential oil pollution problems on the great lakes of Africa for a conference organized by the International Association of Theoretical and Applied Limnology. A fellow of the British Institute of Biology and the Institute of Petroleum, Dr. Baker has published numerous papers in the scientific literature on the recovery of impacted shoreline ecosystems.

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Copies of this report or the review
"Natural Recovery of Cold Water Marine Environments After an Oil Spill"
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CRS Report for Congress

Oil in the Ocean: The Short- and Long-Term Impacts of a Spill

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OIL IN THE OCEAN: THE SHORT- AND LONG-TERM IMPACTS OF A SPILL

SUMMARY

This report describes the short- and long-term impacts of an oil spill. The short-term impact is the incident as generally portrayed immediately following the spill, and the long-term impact is the life cycle of the spilled oil itself. Not surprisingly, the impacts are often different. The media presentation is commonly one of a catastrophic occurrence, and a major oil spill is indeed that. Media coverage also tends to focus on the more emotional aspects of destruction to the local environment, to which irreparable harm is often claimed. Rarely does media coverage convey the fact that oil is a natural substance, and that natural processes, over time, will do much to remove it.

Oil that is spilled or seeps naturally into the ocean is eventually accommodated by natural physical, chemical, and biological processes, including spreading, evaporation, solution, emulsification, tar lump formation, photochemical oxidation, microbial degradation, uptake by organisms, and sedimentation and shoreline stranding. Factors particular to each spill influence the effectiveness of these processes, and determine the severity of the ecological impact. Although human intervention can help to make a shoreline look clean, it has rarely been very effective in removing oil, and improper clean-up methods can be detrimental to the ecological restoration of the area. Historically, it has been unusual for more than 10 to 15 percent of the oil to be recovered from a large spill.

The life cycles of six major oil spills were chosen for examination because they occurred sufficiently long ago for long-term effects to have become apparent and for attention from the media to have long subsided. Because they are still being studied, the *Exxon Valdez* and the *Mega Borg* incidents are not discussed. The six events chosen are the Santa Barbara and Ixtoc I blowouts and the *Argo Merchant*, *Burmah Agate*, *Alvenus*, and *Amoco Cadiz* tanker spills. Each event received extensive media coverage at the time and are still thought of by many as major environmental catastrophes. In fact, the environmental damage and socioeconomic consequences were relatively modest, and, as far as can be determined, of relatively short duration.

The longest residence time spilled oil appears to have in the marine and coastal environment is generally less than a decade—often much less. The major ecological impact comes at the time of the spill or within the first few months. Beyond a few months, most oil is reduced to tarry residues or is chemically detectable in sediments and resident organisms, which may be of scientific interest, but in terms of further ecological impact, likely to be fairly insignificant. Short-term impacts on marine animal life are dramatic but recovery of species populations in almost every case studied has been swift.

Because many physical and biological processes in the marine and coastal environment are poorly understood, it is difficult for scientists to measure the full impacts of an oil spill and sometimes the results appear contradictory.

TABLE OF CONTENTS

INTRODUCTION	1
FACTORS THAT DETERMINE THE SEVERITY OF THE ECOLOGICAL IMPACT	3
Oil Dosage	4
Type of Oil	4
Fresh Versus Weathered Oil	5
Location and Natural Environmental Stresses	5
Damages Due to Clean Up	8
THE BIOGEOCHEMICAL LIFE CYCLE OF OIL IN THE OCEAN	8
Spreading	10
Evaporation	11
Solution	11
Emulsification	12
Tar Lump Formation	12
Sedimentation and Shoreline Stranding	12
Photochemical Oxidation	14
Microbial Degradation	14
Uptake By Organisms	15
THE SHORT-TERM IMPACT	16
The News Media and Damage Perceptions	17
<i>Argo Merchant</i>	18
Santa Barbara	19
Campeche Bay/Ixtoc I	22
<i>Burmah Agate</i>	24
<i>Alvenus</i>	25
<i>Amoco Cadiz</i>	27
CONCLUSIONS	32
EPILOGUE	34

OIL IN THE OCEAN: THE SHORT- AND LONG-TERM IMPACTS OF A SPILL

INTRODUCTION

Crude oil is made by nature and has long been part of the environment. Oil forms largely from the burial and transformation of marine organisms under heat and pressure over geologic time. Most of the oil that ever formed was not trapped in reservoirs, but seeped to the surface where it was decomposed, digested, and recycled. Many of these seeps are small, but many are not. A significant amount of this seepage and recycling occurs in the marine environment. Although difficult to quantify, it is estimated that on the order of 1.5 million barrels of oil enter the oceans from natural seeps each year, and even this amount may be an order of magnitude too low.¹ In any event, oil has been common to the oceans for hundreds of millions of years, long before the advent of humans. When oil seepage or oil spills occur, natural organisms and natural chemical processes act to decompose it. For example, an average liter of seawater normally contains about ten hydrocarbon decomposing bacteria, but after an oil spill their population densities can reach 50 million per liter.²

As it comes out of the borehole, crude oil has never been of much practical use. In a refinery, this unpretentious raw material is converted into hundreds of products and chemicals essential to maintaining the quality of life in modern society. Some of these refined products are less common and more toxic than crude oil and are also commonly transported by tanker. A spill of refined products can differ considerably from a spill of crude oil, as will be shown.

Human activities involving oil in the marine environment include drilling for and producing crude oil offshore and transporting both crude oil and refined products by tanker. These activities rarely take place in a pristine environment. Human beings have had an impact on the ocean, particularly coastal areas for many years. Consequently, a return to pre-spill conditions can easily mean a return only from a very disturbed to a less disturbed condition. In addition, "normal" or "baseline" conditions are not static because the environment is dynamic and constantly changing, not only from human disturbance, but also from natural change. Many physical and biological processes are occurring in the marine and coastal environment that are only poorly understood. For these reasons, it is particularly difficult for scientists

¹ National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, 601 p.

² Coastal Zone Management, June 20, 1990, p. 7.

to measure the full impacts of an oil spill and sometimes the results appear contradictory.

A major oil spill is both tragic and (as long as the world is based largely on a petroleum economy) inevitable, because no technology is without environmental cost and none is fail-safe. A recent study performed for the State of Alaska determined that a catastrophic spill in the Valdez tanker trade, similar in magnitude to the *Exxon Valdez* spill in Prince William Sound (the *Exxon Valdez* spilled 258,000 barrels), would occur on the average of once every 13 years, or about once every 11,600 transits, under the circumstances that existed prior to the spill.³ Thus, by those estimates, the *Exxon Valdez* spill occurred within the predicted time frame. Improvements already accomplished, and further improvements to be accomplished, will likely extend the average recurrence interval considerably.

Following the *Exxon Valdez* spill, leaders in the House and Senate announced that comprehensive oil pollution liability and compensation legislation was a priority. There appears to be a general consensus among the Administration, Congress, and the oil industry that such legislation is necessary. Subsequently, the House has passed H.R. 1465 and the Senate passed S. 686, which are now in conference (the conferees reached agreement on July 26, 1990). These bills would internalize the immediate costs of pollution cleanup and damages within the oil-handling industry (although ultimately they would be borne by consumers). Also the bills would offer financial protection to a number of industries and businesses affected by a spill, including the fishing and recreation industries that are characterized by many small participants and are subject to natural and seasonal variations. In addition to providing a framework for dealing with a spill event after it occurs, the legislation also addresses spill prevention through technology and operational requirements and safety provisions. These include the establishment of an oil spill research and development program and tanker operation and design regulations including provisions relating to alcohol and drug abuse, access to the National Drivers Registry, and requirements for double hulls. Taxing provisions to establish a \$1 billion compensatory fund were passed as part of the Reconciliation Act (P.L. 101-239, Section 7505. (For a summary of the issues addressed in the differing provisions of the House- and Senate-passed bills, see CRS Issue Brief 89082, *Oil Pollution Liability and Compensation Legislation After the Exxon Valdez Oil Spill*.)

It is possible to think of an oil spill as having two life cycles. One is the short-term life cycle generated by the human environment, including the media and other interests (primarily affected individuals, State and local governments, and environmental groups); the other life cycle is the biogeochemical cycle of carbon and its compounds in the natural environment.

³ Spill: The wreck of the *Exxon Valdez*. Report of the Alaska Oil Spill Commission, Jan. 1990, Executive Summary, p. 4.

The former is generally given great attention; the latter is rarely considered outside of the technical and scientific literature. Consequently, the perceived impact of an oil spill may be little related to what ultimately happens to the oil or to the interaction that the oil has on the affected area, but rather to what is said about the event at the time. This is significant because the public and policy decision makers can be influenced by perceived impacts of events.

FACTORS THAT DETERMINE THE SEVERITY OF THE ECOLOGICAL IMPACT

A great number of factors, individually or in combination, govern the effects that an oil spill may have on marine life. Some spills may have a relatively minor effect compared to others which may be much more locally damaging. The biological damage that results depends largely on the following factors:

1. The dosage of oil and the duration of the exposure;
2. The type of oil involved, particularly with respect to its content of the more toxic aromatic compounds;
3. Whether the oil is in a fresh, weathered or emulsified form;
4. Whether a coastal, estuarine or open ocean area is involved, and whether it is a nesting or wintering ground for sea birds, migration route, etc.;
5. Natural environmental stresses imposed by meteorological or oceanographic parameters such as fluctuations in salinity, water temperature, wind conditions, etc.;
6. The season of the year with respect to whether organisms are dormant or actively feeding and reproducing;
7. Whether adult or juvenile forms are involved;
8. Whether the oil is in solution, suspension, or absorbed onto particulate material;
9. Distribution in the water column, such as whether plankton, pleuston, nekton or benthos are involved and which species;
10. The effects of oil on competing biota;
11. The ecosystem's previous history of exposure to oil or other pollutants; and

12. Clean-up procedures, if any, that have been used, and, particularly, whether chemical agents have been used.⁴

Oil Dosage

Many of these factors are interrelated. The dosage of oil an area receives depends primarily on the size of the spill and the elapsed time before it is dispersed. Physical constraints on the spill, such as embayments, do not allow oil to disperse rapidly and, thus, effective dosage will be increased. The portions of the oil that sink, float, and dissolve also determine the dosage. In general, the biological damage is much more severe if the spill occurs in a coastal or estuarine environment, especially if the intertidal zone is affected, than if it occurs in the open ocean. This greater damage occurs because there are generally many more diverse habitat types and numbers of organisms in the near-shore areas and because of the presence of the sensitive juvenile stages of many species. By comparison, the reported biological damage in the open ocean has been minimal, with the most visible impacts related to oiled seabirds and marine mammals. Although only a few studies have been conducted, no evidence has been found that plankton populations have been significantly altered by oil spills on the high seas.⁵ Even if a large number of algal cells were affected during a spill, regeneration time of the cells (9 to 12 hours), together with the rapid replacement by cells from adjacent waters, would likely obliterate any major impact on a pelagic phytoplankton community.⁶

Type of Oil

Offshore spills can involve both crude oil and refined products. While OCS production spills would primarily involve crude oil, tanker spills could involve either crude oil or refined products. Generally, refined products such as fuel oil or gasoline have greater concentrations of toxic components than crude oil, and spills of refined products would likely have a greater ecological impact. However, because lighter refined products such as fuel oil or gasoline are more volatile than crude oil, the visual impact of the spill will be of shorter duration and the likelihood of shoreline impacts will be less. The greater biological impact from refined products has been cited as one reason

⁴ IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP). Impact of Oil on the Marine Environment. Reports and Studies No. 6. Published by the Food and Agriculture Organization of the United Nations, Rome, 1977, p. 54.

⁵ National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, p. 442.

⁶ Ibid., p. 404.

for the severity of the observed effects of the well-studied West Falmouth, MA spill in 1969, which released about 4,000 barrels of No. 2 fuel oil into the waters of Buzzards Bay, and surrounding marsh areas (near Woods Hole Oceanographic Institution). No. 2 fuel oil is enriched in aromatics, some of which are created in the refining process. On the other hand, studies of a large fuel oil spill (54,000 barrels) in Japan's Inland Sea in December 1974 indicated no evidence of lasting damage.⁷ The Inland Sea seemed particularly vulnerable to contamination because it is relatively shallow and circulation is restricted, but data indicated that populations of marine organisms and water quality returned to normal after three months.

No. 2 fuel oil was also involved in the spill of the Greek-flagged tanker *World Prodigy* which ran aground on Branton Reef just outside of Narragansett Bay, Rhode Island on June 23, 1989. The spill released approximately 6,900 barrels of fuel oil into the coastal waters of Rhode Island. Some shoreline impact occurred and the Rhode Island fishing industry was disrupted for at least a week, but the majority of the oil evaporated. Two weeks after the spill occurred the general scientific consensus was that any longer-term damage would be minimal due to the rapid dissipation of the oil and timely cleanup response.⁸

Fresh Versus Weathered Oil

The longer a spill is exposed and weathered before it enters a sensitive area, the fewer harmful compounds it will contain. Generally, the lighter and more soluble compounds, which are the more toxic, are removed and degraded early in the weathering process, as will be shown in the following section on the geochemical life cycle. Heavy tarry residues have much less severe biological impact.

Location and Natural Environmental Stresses

The climatic conditions and location of a spill area influence the ecological impact. The effects of oil spilled in a cold marine environment, such as the North American Arctic, might be much more serious and long lasting than in a more temperate area for the following reasons:

1. Cold temperatures do not permit rapid evaporation of aromatics in oil, thus allowing more of these toxic hydrocarbons to enter solution

⁷ Chemical and Engineering News. No Lasting Damage From Japanese Oil Spill, Oct. 20, 1975, p. 13.

⁸ U.S. Congress. Senate. Committee on Environment and Public Works, Subcommittee on Environmental Protection. Three Recent Oil Spills. Hearing, July 13, 1989, U.S. Govt. Print. Off., Washington, 1989, p. 62.

in sea water even though the solubility of these compounds is lower at low temperatures;

2. The rate of bacterial degradation and other processes of weathering are comparatively slower at very cold temperatures; and
3. The marine biota of polar regions are generally long-lived, have low reproductive potentials, and do not have wide-ranging dispersal stages.⁹

On the other hand, biodiversity is lower and fewer species would be affected. In general, however, recovery from an oil spill in polar regions would likely be slow.

Another reason that the location of a spill is an important factor in determining the impact is that biota vary greatly from area to area. For example, the habitat of the East Coast of the United States is geologically and ecologically quite different from the West Coast, and the Louisiana coastal environment is not like that of Alaska. Different organisms react to oil pollution in different ways. What kills one species may have little or no effect on another, thus upsetting prey and predator relationships.¹⁰ Individuals within a species may differ--eggs, larvae, and newly molted individuals have different sensitivities to the same level of pollution.

Location is also important in terms of the physiography and physical energy of the area. For example, a spill off a low-energy marshy area can have much longer lasting effects than a spill on a high-energy rocky coastline. Oil from the *Amoco Cadiz* that entered quiet backwaters was still present in sediment two years later, whereas by that time oil was no longer found in the sediment of some of the more energetic offshore areas.¹¹

The season of the year a spill occurs is an important factor. Most marine organisms show natural seasonal variations that are related to yearly cycles as well as year to year variations. For example, if a spill occurs during the season when sea birds are nesting, bird mortality would be much higher than at other times the year. If a spill enters an estuary when salmon smolts are going to sea or during a salmon run, much more severe impacts are

⁹ Boesch, D. F., C. H. Herschner, and J. H. Milgram. *Oil Spills and the Marine Environment*. Ballinger Publishing Co., Cambridge, MA, 1974, 114 p.

¹⁰ IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, *Impact of Oil on the Marine Environment*, p. 54.

¹¹ Gundlach, E. R., P. D. Boehm, M. Marchand, R. M. Atlas, D. M. Ward, and D. A. Wolfe. *The Fate of Amoco Cadiz Oil*. *Science*, July 8, 1983, p. 122-129.

likely.¹² Larvae that float near the surface of the water, and newly set oyster spat will probably be killed if a spill occurs during this stage of their life cycles, whereas these organisms are less vulnerable during later stages of development. Had the January 1969 blowout spill at Santa Barbara, CA happened earlier, some nursing pups of sea lions and elephant seals may have succumbed after ingesting oil coating their mothers teats, and sea bird populations would have been greater (likely resulting in more mortalities).¹²

Oceanographic and meteorological factors such as wind conditions and currents in the spill area vary from day to day, and may drive floating oil either onshore or offshore. Currents and wave action combine to spread and dilute the spilled oil, thus reducing its potential impact. On the other hand, wave action may intensify problems especially near shore, as apparently occurred at West Falmouth. At West Falmouth, onshore winds churned oil with sediments and drove the oil ashore into the surrounding marshlands. The oiled sediments and marshlands then became a reservoir of oil for several years.¹⁴ Recognizable chemical components of the fuel oil persisted in the sediments for at least 8 years.¹⁶

At Santa Barbara, the spill occurred during a period of heavy storms that brought flood waters bearing great amounts of sediment into the coastal waters. The sediment-laden fresh water provided an adsorptive surface for the spilled oil causing much of it to settle to the bottom rather than reaching shore.¹⁶ Sedimentation is advantageous to intertidal life because this may prevent the oil from reaching the intertidal zone, but it may be detrimental to benthic life.¹⁷

¹² National Academy of Sciences, Ocean Affairs Board. Petroleum in the Marine Environment. National Academy Press, Washington, D.C., 1975, p. 83.

¹³ Boesch, et. al., Oil Spills and the Marine Environment, p. 38.

¹⁴ Blumer, M., H. L. Sanders, J. F. Grassle, and G. R. Hampson. A Small Oil Spill. Environment, v. 13, no. 2, 1981, p. 1-12; and Sanders, Howard L. The West Falmouth Spill. Oceanus, fall 1977, p. 15-24.

¹⁵ National Research Council, Oil in the Sea: Inputs, Fates, and Effects, p. 551.

¹⁶ Drake, D. E., P. Fleischer and R. L. Kolpack. Transport and Deposition of Flood Sediment, Santa Barbara Channel, California. In Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill 1969-1970, v. 2, R. L. Kolpack ed. Allan Hancock Foundation, 1971, p. 181-217.

¹⁷ Blumer et. al., A Small Oil Spill, p. 1-12.

Damages Due to Clean Up

An improper method of cleaning up an oil spill can increase the impact of oil pollution rather than diminish it. At sea, mechanical methods are considered the least damaging to the environment. These methods include the use of booms and skimmers or the spreading and retrieval of absorbent material. Sinking agents acting in the same way as naturally turbid water, transfer the effects from intertidal coastal areas to offshore bottom-dwelling fauna, and may extend the duration of the impact. The use of dispersants is controversial and has been shown to be helpful in some cases and harmful in others, depending on the toxicity of the dispersed oil and the nature of the particular organisms one is intending to protect. Low-toxicity dispersants have the advantage of preventing oil from washing ashore, soiling beaches and killing intertidal organisms, but pose an additional burden on the assimilative capacity of the marine environment. (For a discussion of cleanup technologies see CRS Report For Congress, 90-146 SPR, Oil Spill Response Technologies.)

Onshore, cleaning a soiled marsh area may prolong its recovery rather than aiding it. Scrubbing soiled rocky coastlines with hot water to restore their beauty may be done at the sacrifice of the surviving organisms along the shoreline. Providing nutrients to soiled areas to stimulate natural bioremediation is a new technique that would take longer than scrubbing to achieve a clean substrate but is less environmentally damaging.

With such a complex interaction of variables, it is not possible to predict accurately the severity of the ecological impact of an oil spill. However, it would appear predictable that long-term effects, if any, would be minimal. Further insight into the latter can be gained, however, by examining the fate of petroleum in the marine environment.

THE BIOGEOCHEMICAL LIFE CYCLE OF OIL IN THE OCEAN

When petroleum enters the ocean, it immediately begins to undergo a series of weathering and biological processes that distribute the material in the environment and alter its physical and chemical nature. The ultimate result of these processes is the complete removal of essentially all traces of the original crude oil and the geochemical recycling of the carbon. The time involved in this chemical recycling process can range from a matter of minutes and hours for the removal of some components of crude oil to a few years for other components. Figure 1 summarizes the fate of oil in the ocean superimposed with a general indication of the time frame of each process. The width of the lines generally indicates when that process is primarily operating and its relative magnitude compared to the others.

In general, during the aging of a spill in the open ocean, the relative influence of the various dispersive and degradative processes shifts from rapid physical effects to slower chemical and biochemical modifications. Initially the

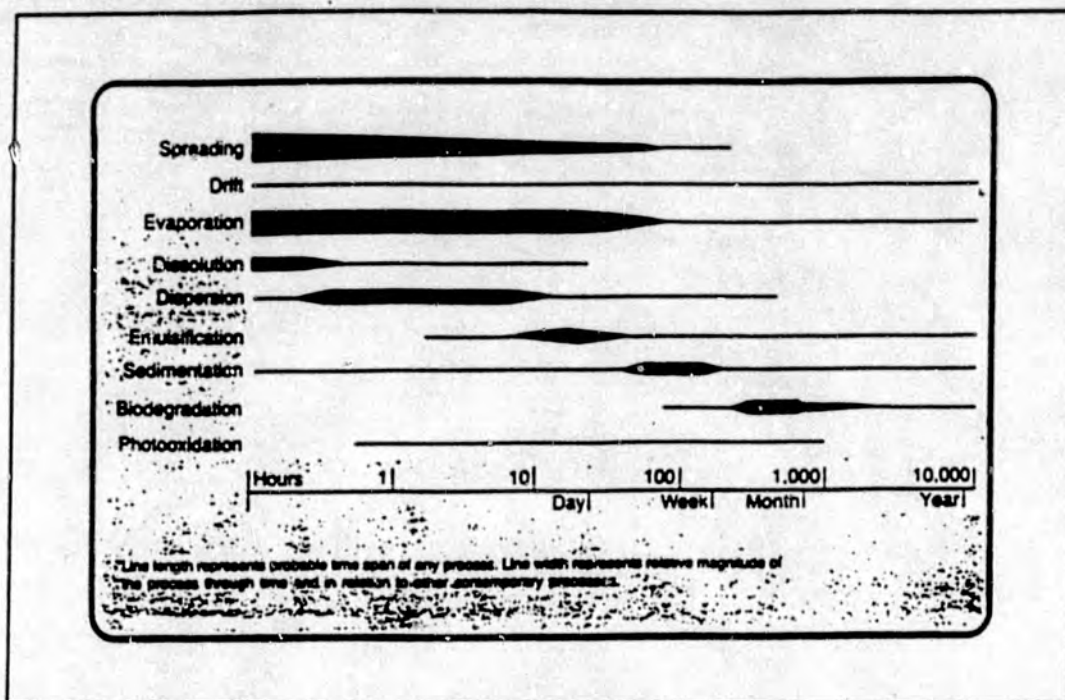


Figure 1. Approximate time span and relative magnitude of processes acting on spilled oil.

Source: Exxon Production Research Company

oil spreads rapidly through the combined action of gravity and surface chemistry. As the surface to volume ratio increases there is greater exposure to air, sunlight, and sea water. Spreading, evaporation and solution are the primary physical dispersive processes while photooxidation and biological degradation begin to assume a more dominant role as exposure time increases. Eventually, a relatively mature phase is reached when more refractory or resistant tarry residues predominate. Figure 2 is a stylized representation showing various pathways without attempting to quantify reaction rates. Reaction rates are poorly known as they depend on much the same interacting variables that determine the severity of the ecological impact described previously.

The following sections consider the physical, chemical, and biological processes that operate during the life cycle of an oil spill. The physical and chemical processes involved include spreading, solution, evaporation, emulsification, photochemical oxidation, tar lump formation, and sedimentation. Biological processes include degradation by microorganisms and uptake by larger organisms with subsequent metabolism, storage, and discharge. In addition, concerns that have been raised over the possibility of food chain magnification are reviewed.

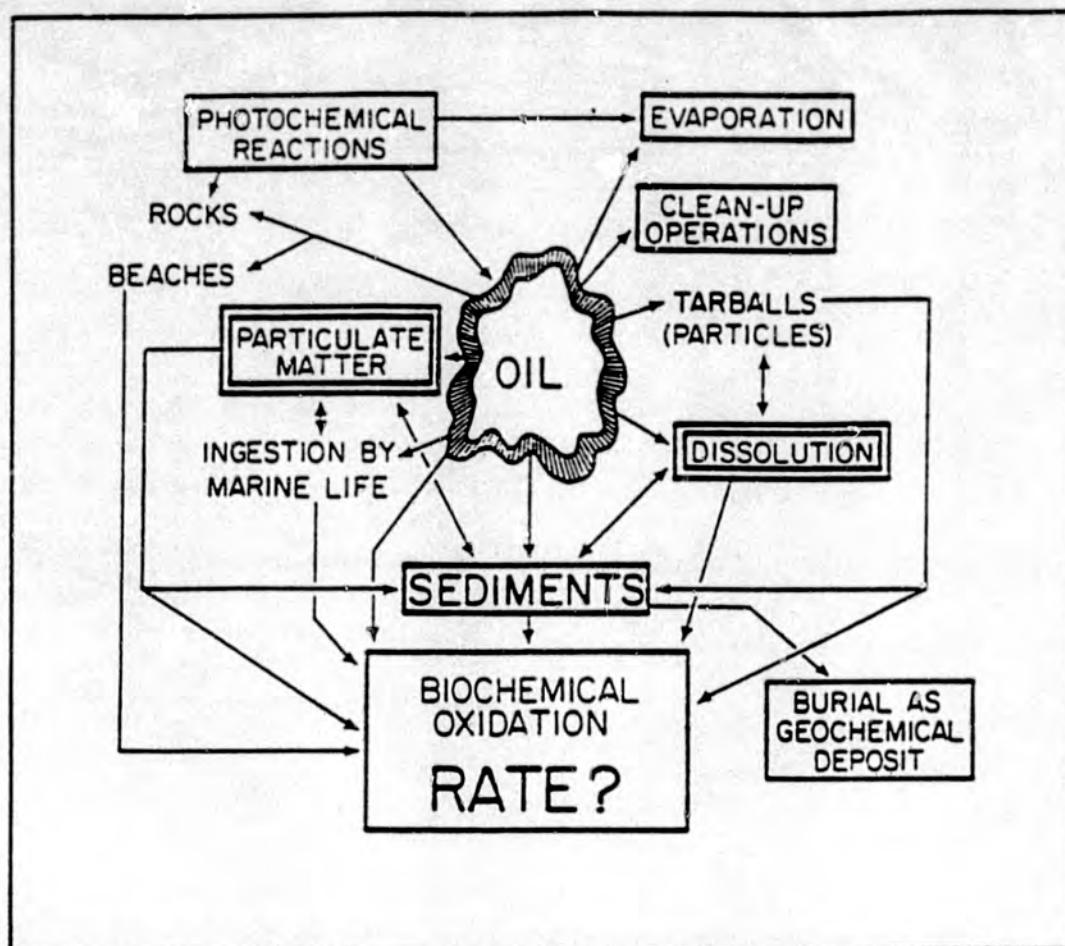


Figure 2. Fate of oil inputs to the marine environment.
Source: Oceanus, v. 20, no. 4, Fall 1977.

Spreading

Spreading begins as soon as petroleum is released into the ocean. Ultimately the area occupied by an oil slick is dependent on the volume spilled. Initially the physical process of spreading is controlled by gravitational effects which are influenced by wind, waves, and currents. After a few hours, the chemical and physical nature of the oil such as viscosity and surface tension become the controlling factors on the extent of spreading. The polar, surface-active constituents, containing nitrogen, oxygen, and sulfur, are influential in spreading a spill into very thin layers that approach monomolecular dimensions at the edges of the slick. Even massive spills eventually spread into thin layers and become fragmented by wind and waves into patches and windrows.

Spreading is important in the life cycle of a spill in that it greatly increases the surface area of the oil, thereby increasing its exposure to air, sunlight, and underlying water. This enhances the rate and effect of the other processes. However, spreading also reduces the effectiveness of mechanical recovery equipment.

Evaporation

Evaporation is the process in which low to medium weight crude oil components with low boiling points volatilize into the atmosphere. Evaporation is greatly enhanced by spreading. The rate of evaporation is greatest during the early stages of a spill. It appears that most hydrocarbons of around twelve carbon atoms or less are lost through evaporation within the first few days, with heavier hydrocarbons, up to twenty carbon atoms, evaporating over a few weeks. Through the selective processes of evaporation, aided by solution, the specific gravity of the oil increases. As evaporation progresses crude oil begins to resemble Bunker C (heavy) oil in composition. As a spill matures further, these processes contribute to the formation of thick sludge, tar balls, and eventually to sinking if the residual oil becomes denser than sea water.

For the Ixtoc I blowout, evaporation was the predominant weathering mechanism, resulting in a nearly equal loss of saturated and aromatic hydrocarbons with low boiling points.¹⁸ Total evaporation loss is difficult to measure. Indirect evidence from compositional changes and laboratory studies indicate that 20 to 40 percent of an "average" crude oil spread over the sea surface can be removed by evaporation. Researchers studying the *Amoco Cadiz* tanker spill estimated that about 30 percent of the oil was removed through evaporation.¹⁹

Solution

Solution is the physical process by which the low molecular weight hydrocarbons, as well as some of the more soluble nonhydrocarbon constituents, enter the water column. The water soluble fractions of crude oil include light alkanes, such as propane, through isopentane and the light aromatics, benzene, toluene, and xylene. The acute toxicity of an oil is largely related to its soluble di- and tri-aromatic hydrocarbon content.²⁰ Even though solution starts as soon as the oil is released into the sea, it can continue for a long period as more soluble degradation products continue to be formed from biological and chemical oxidation. The rates at which soluble

¹⁸ Boehm, P. D. et. al. Physical-Chemical Weathering of Petroleum Hydrocarbons from the Ixtoc I Blowout--Chemical Measurements and a Weathering Model. In Proceedings, 1981 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 453-460.

¹⁹ Gundlach, E. R. et al., The Fate of *Amoco Cadiz* Oil, p. 122-129.

²⁰ IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, Impact of Oil on the Marine Environment, p. 25.

components are removed from crude oil are poorly known. Over short periods of time, evaporation will remove highly soluble components more rapidly than solution. Evaporative weathering causes an equivalent depletion of saturated and aromatic compounds with low boiling points, whereas solution preferentially depletes low-boiling aromatics relative to saturated compounds, because of the much greater solubilities of the aromatics. Over a longer period, the solution rate will decline because of the lower solubility of the remaining high molecular weight components.

Emulsification

Most of the components of petroleum are relatively insoluble in seawater and in rough seas tend to form emulsions. Emulsions are of two types: oil-in-water emulsions where fine particles of oil are incorporated into the seawater, and water-in-oil emulsions where the floating emulsion contains 30 to 80 percent water. The latter are formed particularly from heavy crudes and are commonly referred to as "mousse." Emulsification promotes solution of the more soluble components by increasing surface area contact between oil and water. The eventual fate of oil-in-water emulsions appears to be dissolution in the water column or association with particulate matter and eventual biodegradation or incorporation in sediments. Mousse has been suggested as a source of pelagic tar lumps. Mousse can sink or become stranded on shore before degradation is completed.

Tar Lump Formation

The weathering processes described above can lead to the formation of residual lumps of tar which are much slower to degrade. These have been observed in the open ocean and can be a particular annoyance when washed up on beaches. At this stage of the weathering process, very little material lighter than 15 carbon atoms remains. Most tar lumps consist of paraffinic hydrocarbons of up to forty carbon atoms, and frequently contain waxy inclusions. These remain fairly persistent in the marine environment. For example, it was estimated that five to ten percent of the pelagic tar found in the eastern Gulf of Mexico four years after the Ixtoc I blowout originated from that event.²¹

Sedimentation and Shoreline Stranding

For residual fractions of crude oil to sink before reaching shoreline areas, the density must increase sufficiently. This generally occurs through loss of lighter components by evaporation and dissolution and/or sorption of liquid or dissolved components onto denser particulate material. Sedimentation is

²¹ Oil Spill Intelligence Report, v. VI, no. 24, June 24, 1983.

dependent on the availability of dense particulate matter to act as nuclei. This process can be especially important in removing petroleum from the water column in near shore areas or estuaries where there is generally a high concentration of suspended sediment. The chemistry of interactions with particulate material depends on the locale and the composition of the materials. Fine grained clay minerals can remove dissolved petroleum through absorption and adsorption. Sorption increases with salinity and decreases with temperature. Rough seas in shallow waters also stir up sand, silt, clay, and shells on which petroleum can be absorbed or agglomerated.

The further movement and fate of oil in bottom sediments is poorly understood. A succession of chemical studies following the barge spill of No. 2 fuel oil in Buzzards Bay, Massachusetts, in 1969, showed that oil trapped in subtidal sediments continued to expand in areal extent for several years after the spill.²² Presumably various suspension and resedimentation processes occurred aided by current movement and reworking of surface sediments. In addition, there was an extremely slow rate of degradation of the fuel oil in the sediments with recognizable components present more than eight years later.²³

Investigations following the *Amoco Cadiz* spill off the coast of France confirmed that oil persistence in subtidal sediments appeared to correlate with the physical energy of the particular site and the type of sediment. For example, of a total of 56,000 barrels of crude oil hydrocarbons estimated to have become incorporated into subtidal sediments in the Bay of Lannion and the Bay of Morlaix during the first month of the spill, only 13,000 barrels were present four months later. After an additional year this had declined to less than 6,000 barrels and little or no oil remained in the sediment after two and one half years.²⁴ On the other hand, fine grained sediments in lower wave energy, sheltered interior areas of Aber Wrac'h were still found to contain oil after three years, and the heavily-oiled marsh areas, in general, took an additional 2 to 5 years to recover fully.

Shoreline stranding is one of the more distressingly visible intermediate fates of petroleum from an offshore spill. Recovery times depend on the extent of the initial impact, the persistence of the oil, inherent factors of the biological community governing its resiliency, and the extent of biological interactions such as predation, parasitism, and competition. In the case of the high-energy rocky shores at Santa Barbara, California, recovery time was on the order of weeks to a few months, whereas soft-bottom offshore areas and marsh ecosystems such as Ile Grande, France were affected for several

²² Sanders, Howard L. *The West Falmouth Spill--Florida, 1969*. *Oceanus*, v. 20, no. 4, fall 1977, p. 15-24.

²³ *Ibid.*, p. 24.

²⁴ Gundlach, E. R. et. al. *The Fate of Amoco Cadiz Oil*. *Science*, v. 221, July 8, 1983, p. 122-129.

years. Oil presumably from the Ixtoc I spill, in the form of tar mats consisting of sediment and mousse, was periodically uncovered by storm action along the south Texas coast for about a year. A field experiment of the persistence of stranded crude oil and mousse on seven shores around the coast of Great Britain showed that the residence times ranged from a few days to one year.²⁵

Photochemical Oxidation

Photochemical oxidation is the process whereby energy from sunlight in the presence of oxygen transforms hydrocarbons into oxygenated compounds (e.g., carboxylic acids, benzoic acid, alcohols, ketones, phenols), with the general result that the oxidation products are more soluble in water than the original compounds. Some products have been found in the laboratory to be more toxic than the parent compounds. Observers studying the *Amoco Cadiz* spill (a tanker spill off the coast of France in 1978) found photooxidation products in environmental samples similar to those found in laboratory studies. The rate of oxidation of hydrocarbons varies with their chemical nature. In photochemical processes, the optical density of the oil, particularly in the ultraviolet, is an important variable. Investigators have made experimental studies of the actual decomposition rates of slicks by photolysis. It was found that photolysis can initiate sufficient oxidation to decompose a thin slick in a few days.²⁶

Microbial Degradation

As the residence time of oil in the ocean increases, biological processes begin to operate and rapidly gain in significance. Hydrocarbon decomposing microorganisms are ubiquitous. Over 90 species of microorganisms (bacteria and fungi) capable of subsisting on petroleum and, therefore, capable of degrading it by biological oxidation, have been identified.²⁷ Microbial processes also transform hydrocarbons to more soluble oxidized products, which eventually are completely oxidized to carbon dioxide and water.

²⁵ Little, D. I. and D. L. Scales. The Persistence of Oil Stranded on Sediment Shorelines. In Proceedings, 1987 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4452, 1987, p. 433-438.

²⁶ National Academy of Sciences, Petroleum in the Marine Environment, p. 48.

²⁷ IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, Impact of Oil on the Marine Environment, p. 29.

The extent of microbial degradation in the sea is dependent upon water temperature and on the absence or dilution of certain volatile fractions in the spill which are bacteriocidal in high concentrations. Nutrient limitation, specifically by nitrates and phosphates, is another major factor in the effectiveness of microbial degradation of petroleum in the marine environment. This was evidently the case following the Mexican Ixtoc I spill, where biodegradation was nearly inoperative in the open ocean. The primary reason appeared to be related to the low concentration of nutrients in the underlying water. This contrasts with other spills, such as the *Amoco Cadiz* tanker incident, where microbial degradation played a significant role, removing 73,000 barrels of oil while still at sea.²⁸

Physical factors limit oil decomposing bacteria from removing more than about one-third of spilled crude oil within 100 days.²⁹ These limitations include (1) the presence of only about 10 hydrocarbon decomposing bacteria in an average liter of seawater prior to a spill, (2) the dwindling availability of oxygen as the spill area grows, and (3) the lack of oil/water boundary action (where microbial degradation occurs) in areas of low wave action. Oil decomposing bacteria multiply after a spill occurs, reaching peak densities of 50 million per liter, but growth is slow at first. Microbial degradation is also temperature dependent; it takes approximately four times longer at 4°C than at 18°C.³⁰

Uptake By Organisms

Petroleum hydrocarbons become available for uptake by marine organisms as dissolved or dispersed materials, absorbed onto particulate material, or as small floating tar balls. Hydrocarbons enter the marine food web by several routes: direct uptake of dissolved or dispersed material, ingestion of the contaminated particulate material, or passage into the gut of fish which gulp or drink water.³¹ A considerable portion of petroleum is absorbed onto particulate matter.

In some cases the biota may be severely affected by the presence of oil, but they are not a major reservoir for spilled oil. However, they may act as temporary storage sites or transfer points. Marine animals are also not major

²⁸ Gundlach, E. R. et. al. *The Fate of Amoco Cadiz Oil*, p. 122.

²⁹ LeBlanc, Leonard A. *Advanced Technology, Why Oil Decomposition Rates Are Hard to Improve*. Offshore, Apr. 1990, p. 17.

³⁰ Ibid.

³¹ IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN Joint Group of Experts on the Scientific Aspects of Marine Pollution, *Impact of Oil on the Marine Environment*, p. 38.

factors in influencing the distribution of spilled oil. After petroleum hydrocarbons are taken up by an organism, they may be excreted unchanged, metabolized, or stored with possible elimination at a future time. Excreted fecal matter containing oil is generally more dense than seawater, hence there is some distribution of petroleum hydrocarbons through the water column and sedimentation from grazing organisms.

An additional concern that has been raised in association with the uptake of petroleum hydrocarbons by marine organisms is that of biological magnification. It has been suggested that petroleum hydrocarbons transfer through marine food webs, becoming more and more concentrated, in a manner similar to that of other persistent chemicals. Some researchers have found that many marine organisms may accumulate petroleum hydrocarbons in their tissues, and that a certain portion may persist throughout the life of an organism. However there is very little evidence, if any, of increased accumulation in the higher predatory members of the food web.³²

On the other hand, another aspect of oil in the marine environment is its "benefit" as a source of food. When oil is biodegraded, primarily by microorganisms, it serves as a source of nourishment at the bottom of the food chain. Other organisms grazing on the oil ingesters are nourished by them, as are further predators along the food chain. Thus, in this respect, oil is no more of a pollutant than any other organic material serving as a source of food. In fact, there are chemosynthetic ecosystems based on petroleum oozing from deepwater seeps in the Alaminos Canyon area on the Texas continental slope east of Galveston.³³ The photosynthesis that these ecosystems with their succession of predators depend on is not today's sunlight, but the photosynthesis that occurred millions of years ago, which helped create the petroleum.

THE SHORT-TERM IMPACT

A major oil spill is a major media event at the time of its occurrence. This section will examine the life cycles of six major oil spills that occurred

³² Connell, D. W. and G. J. Miller. Petroleum Hydrocarbons in Aquatic Ecosystems--Behavior and Effects of Sublethal Concentrations: Part I, CRC Critical Reviews in Environmental Control. Dec. 1980. Reported in Minerals Management Service, Final Environmental Impact Statement, Proposed Apr. 1984 North Atlantic Outer Continental Shelf Lease Offering, p. 286; and National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, p. 6.

³³ Ocean Science News, Apr. 10, 1990, p. 6.

sufficiently long ago for their "long-term"³⁴ effects to have become apparent and for their attention from the media to have long since subsided. The six events are the Santa Barbara and Ixtoc I blowouts and the *Argo Merchant*, *Burmah Agate*, *Alvenus* and *Amoco Cadiz* tanker spills. All of these were major spills, and except for the *Amoco Cadiz*, which foundered off the coast of France, all affected U.S. waters (even though the Ixtoc I blowout occurred in Mexican waters). Each of the events received extensive press and television coverage at the time and are still widely recalled as major environmental catastrophes that caused considerable socioeconomic loss. In fact, the environmental damage and socioeconomic consequences were relatively modest, and, as far as can be determined, of relatively short duration.

The News Media and Damage Perceptions

A number of investigators have probed the influence on the public of media coverage of oil spills and other events. For example, investigators studying the Santa Barbara spill concluded that the frequency and nature of reporting an oil spill could be predicted on the basis of the geographical proximity of the media to the event.³⁵ They also showed that an occurrence receives much coverage close to its date of origin, and subsequent related happenings received comparatively little nonlocal coverage.

Initial reporting often focuses on the more "newsworthy" elements of events, e.g., the threat to the health or environmental values of society. For example, media coverage of medical wastes found on beaches on Long Island and northern New Jersey in July 1988 caused beach scares resulting in more than \$1 billion in lost revenues to other resort areas in which no wastes were found.³⁶ In the case of an oil spill, investigations and follow-up studies of actual effects take time, and results often are not available until a year or more has passed. Press coverage of these results is generally minimal and, to a large extent, confined to the more scientific literature. The *Argo Merchant* incident serves as an example.

³⁴ For the purpose of this report, "long-term" is defined to be several years or on the order of a decade or more.

³⁵ Molotch, H. and M. Lester. Accidental News: The Great Oil Spill as Local Occurrence and National Event. *American Journal of Sociology*, v. 81, no. 2, 1975, p. 235-258.

³⁶ Schmitt, Eric. A Summer to Forget on the Jersey Shore. *New York Times*, Sept. 2, 1988, p. B1, B2.

Argo Merchant

On December 15, 1976, the Liberian-registered tanker *Argo Merchant* grounded on the Nantucket Shoals off Massachusetts. Heavy seas during the subsequent week caused the ship to break up, releasing 183,000 barrels of No. 6 residual fuel oil. Attempts to burn the oil were unsuccessful. The heavy oil formed a large slick, which eventually moved out to sea and dispersed. The estimated costs of response to the accident were \$2.7 million.

In a study of media coverage of the *Argo Merchant* grounding and oil spill, researchers found that public perceptions of local damages presented an interesting and intriguing paradox. There is general agreement among post-spill investigations on the absence of serious economic damages (aside from the ship and cargo) resulting from the *Argo Merchant* incident. Persons in the area economically dependent on tourism, water transportation, and commercial fishing generally reported a good year.³⁷ Fortunately, pollution damage was also small.³⁸ There was little evidence of impact on marine fauna or phytoplankton and it was concluded that the spill had little effect on coastal and marine bird populations off the New England coast.³⁹

At the time, EPA Administrator, Russell E. Train, described the event as "the biggest oil spill disaster on the American coast in our history"⁴⁰ and Governor Michael S. Dukakis asked President Ford to declare southeastern Massachusetts a disaster area to qualify it for Federal relief funds.⁴¹ Television coverage featured the visual image of the grounded tanker and the subsequent oil slick.

As the slick broke up and moved out to sea, television coverage was greatly reduced. While a complete assessment of the environmental damage

³⁷ Rappaport, Allen, L. H. Zincone, Jr., and Peter Fricke. The Media and Oil Spills: Does the Press Influence Damage Perceptions? In Proceedings, 1981 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 707.

³⁸ Milgram, Jerome. Being Prepared for Future *Argo Merchants*. MIT Sea Grant Program, Report no. MITSG 77-10, Apr. 1977, p. 13; and Oil Spills: Problems and Opportunities. The MIT/Marine Industry Collegium, Opportunity Brief no. 9, July 1977, p. 9; and The Washington Post, Dec. 15, 1977, p. A 8.

³⁹ National Research Council. Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., 1985, p. 557-561.

⁴⁰ The New York Times, Dec. 22, 1976, p. 1.

⁴¹ The Washington Post, Dec. 22, 1976, p. A 3.

is impossible to obtain, there seems to be general scientific consensus that classifying the incident as an ecological catastrophe had no factual basis.⁴²

The paradox that researchers found when conducting a survey of area residents approximately one year after the spill occurred was that substantially over half still believed that the *Argo Merchant* spill had caused significant economic or ecological damage.⁴³ An analysis of the press coverage showed that it had shifted from an initial position of little or modest damage to one of catastrophe or major disaster, returning to a position of modest or no damage when the oil moved out to sea. This led to the conclusion that once the press portrays a possibility for, or existence of, substantial damages, the subsequent withdrawal of such claims evidently does not alter the perceptions of extensive damage held by a large part of the population.⁴⁴

Again, it should be pointed out that the scientific literature is not without apparent contradiction. Commonly, one investigation reports findings indicating damage of one sort or another, while another study looking at other variables associated with the same event will report different conclusions. These apparent paradoxes are also illustrated in the following case examples.

Santa Barbara

On the 28th of January 1969 on Platform A in the Santa Barbara Channel about six miles southeast of Santa Barbara, California and in 190 feet of water, an incident occurred. The incident, with its widespread media coverage, did much to alter public attitudes toward offshore oil and gas development.

Four wells had already been drilled from the platform and the fifth well, A-21, was nearing completion. Federal requirements for the well had been altered to approve shorter sets of casing pipe than the minimum previously required. On the morning of January 28, the well had reached 3,479 feet and the crew began to pull the drill pipe to run a log (make down-hole instrument readings). As the crew broke out the eighth stand (segment) of drill pipe, fluids from the well blew out through the drill pipe.

The crew attempted to close the blowout preventer inside the well bore hole, but without success. The pressure was so great that some of the

⁴² See for example, Abelson, P. H. Oil Spills. *Science*, Jan. 14, 1977, p. 137.

⁴³ Rappaport, et al., *The Media and Oil Spills: Does the Press Influence Damage Perceptions?* p. 707-712.

⁴⁴ *Ibid.*, p. 711.

equipment failed and the efforts of the crew were hampered by the slick mud-oil-gas mixture and constant danger of fire. After about 15 minutes, the crew succeeded in closing the well using the blind rams of the blowout preventer. However, this was only the first stage of the blowout.

The closure of the well resulted in a huge buildup of pressure within the overlying strata above the oil formation, but where the well had not been cased. Within 30 minutes after closing the well at the top of the casing, oil and gas began to erupt from the seafloor about 800 feet east of the platform. This eruption eventually spread along a zone from 250 feet west of the platform to more than 1,000 feet east of the platform. Faults in the rock formations penetrated by oil and gas under pressure probably helped serve as a conduit. Efforts to control the spill were only marginally successful and seepage from the seafloor still continues at a rate of around 365 barrels annually (comparable to a number of natural marine seeps in the area.)⁴⁶ The initial spill was variously estimated at 10,000 to 77,000 barrels (the Minerals Management Service uses the higher figure) with subsequent seepage of over 28,000 barrels. Containment and cleanup efforts were extensive at the time and, in some cases, led to controversy regarding their overall benefit and efficacy.

The full impact of this spill on the marine and coastal environment is not possible to determine for a number of reasons including: (1) lack of pre-spill information on organisms and populations to provide a reference frame; (2) unusually high runoff from coastal areas which lowered salinity and increased turbidity, thus, masking the effects of the oil spill; (3) unseasonably low temperature further stressing the ecosystem; and (4) many natural seeps in the area which masked any potential long-term effects that could be attributed to the spill.

Among the more visible impacts were the bird mortalities. The California Department of Fish and Game reported the loss of 3,686 birds due to oiling during the first four months of the spill. This is generally regarded as a minimum figure due to unknown numbers lost at sea. Others placed the estimated bird mortality at between 6,000 and 15,000.

Other detrimental impacts were most evident in the intertidal zone where barnacles and surf grass were damaged by physical smothering. Studies indicated that damage to intertidal life was generally proportional to the amount of oil received. In some areas, the local population of acorn barnacles was destroyed, but recolonization readily occurred. Gooseneck barnacles were damaged to a somewhat lesser degree. Some algae were slightly damaged. Kelp was little harmed. However, mysid shrimp that live among the kelp may

⁴⁶ Natural seepage in the Santa Barbara Channel is estimated at 14,600 to 244,500 barrels annually from more than 2,000 seeps. See U.S. Department of the Interior, Minerals Management Service. Federal Offshore Statistics: 1988. OCS Report MMS 89-0082, p. 96.

have been harmed or caused to vacate their usual habitat during the heavy oiling.⁴⁶ Investigators noted limited damage among anemones, abalones, spiny lobsters, mussels, limpets, periwinkles, and starfish. Burrowing fauna generally escaped severe harm. Fish did not appear greatly harmed by the oil, and spawning occurred normally for most species. No fish kills were observed or reported. The limited number of mortalities of marine mammals which were observed at the time of the spill could not be conclusively attributed to effects of the oil.

Some reports suggested spiny lobster and certain finfish harvests may have been depressed for one to several years following the incident. It is difficult to ascribe a cause/effect relationship between the blowout pollution and this observation.⁴⁷ Natural variations in populations of living organisms are such that an abnormal perturbation, such as might occur in response to spilled oil, can only be detected if it is especially extreme. Some of the observed changes in marine biota populations may be more generally related to natural environmental change or reflect the effects of developmental activities onshore. Bird populations did not appear to incur any long-term changes in either behavior or habitat use and most showed signs of recovery by the summer following the event.⁴⁸

The physical impacts of the oil spill dissipated long ago, but the residual psychological scars remain for the local population, and the entire Nation as well. Environmental policy analysts have credited this spill, a discrete physical event, as a major catalyst that precipitated the "environmental decade" of the 1970s. While this attribution may be excessive, a portion of the public still associates negative aspects of offshore oil development with the Santa Barbara oil spill.

The actual effects of the blowout appear to have been limited in both time and extent. Declines in local tourism, shore use, and property values were painful but transitory. Coastal uses rapidly returned to pre-spill levels after the oil was off the beaches. Tar continues to be found on beaches. Although this is known to be from marine seeps, it is frequently perceived by some to be primarily from offshore petroleum development.

⁴⁶ Dept. of Biological Sciences, University of California. Santa Barbara Oil Spill: Short-term Analysis of Macro-plankton and Fish. Prepared for Office of Water Quality Research, Environmental Protection Agency, Contract no. 14-12-534, Feb. 1971, p. 55.

⁴⁷ Mielke, James E. and Eugene H. Buck. Offshore Oil Spills: Is the Shoe Bigger Than the Foot? Congressional Research Service Review, Apr. 1985, p. 16.

⁴⁸ Easton, Robert. Black Tide: The Santa Barbara Oil Spill and Its Consequences. Delacorte Press, New York, 1972, p. 264.

Campeche Bay/Ixtoc I

On June 3, 1979, the Ixtoc I exploratory well in the Bay of Campeche, Mexico, in 167 feet of water, blew out. The trouble began on June 2 when at a depth of 11,857 feet, the well started to lose drilling mud into the rock formations being penetrated. Loss of drilling mud creates an unstable condition since the weight of the mud balances the underground pressure as a defense against blowouts. Despite this problem, the crew drilled further until circulation was totally lost at 11,890 feet.

Several unsuccessful attempts were made to regain circulation, but as the well appeared stable, the crew decided to seal it by withdrawing the drill pipe and inserting a plug. At 3:30 a.m. the well blew out crude oil and natural gas through the drill pipe and caught fire. The explosion and fire destroyed the platform and damaged the stack of drilling pipe and well casing that extended to the seafloor; thus began the largest marine oil spill in the history of offshore drilling or tanker transportation.

About three weeks after the blowout, an attempt was made to close the blowout preventer valves which were still intact on the seafloor under the ruptured pipe. The valves closed but the extremely high pressure caused oil to leak outside the well casing below the blowout preventer. Several attempts were made, with some success, to decrease the flow of oil by forcing large numbers of lead and steel balls into the well head. Next a funnel-shaped "sombrero" was placed over the well head to collect the oil, but this was not very successful, and was eventually damaged in rough seas and removed from the site. Rough seas also hindered other containment and oil recovery efforts.

The measure that finally capped the well on March 23, 1980, was the pumping of mud into two adjacent wells that were drilled directionally into the producing formation to link into the Ixtoc I well. These wells had been started in mid-June and July. After the mud caused the flow of oil and gas to cease, the Ixtoc I well was sealed with several cement plugs. During the 290 days that the spill continued, approximately 3,500,000 barrels of oil entered the Gulf of Mexico.⁴⁹

Dispersants were selectively applied by aircraft to oil masses that threatened Mexican resources. Of special concern was the area extending 20 to 25 miles from shore along 1,000 miles of Mexican coast in major shrimping locations.⁵⁰ The use of dispersants kept oil from coming ashore on Mexican

⁴⁹ Jarnelov, Arne, and Olof Linden. Ixtoc I: A Case Study of the World's Largest Oil Spill. *Ambio*, v. 10, no. 6, 1981, p. 299-306.

⁵⁰ Lindblom, Gordon P., Bruce D. Emery, and Ing. Miguel A. Garcia Lara. Aerial Application of Dispersants at the Ixtoc I Spill. In *Proceedings, 1981 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 259-262.

beaches until hurricane Henri arrived in late September and grounded the aircraft. At that time, oil stranded on the Yucatan shoreline, but lagoons were protected from oiling by the rapid outflow of fresh water from heavy rains. Field investigations indicated that the chemicals effectively dispersed the oil from the surface into the upper 10 feet of the water column by which it rapidly became diluted to low concentrations below acute toxicity thresholds. Limited biological studies during and following the spill did not reveal adverse effects.⁶¹ Shrimp landings in subsequent years were unchanged or greater than previous yearly catches.

Impacts on U.S. resources were limited by the distance oil traveled from the site of the Mexican blowout. An estimated 30,000 to 70,000 barrels of the calculated 3.5 million barrels spilled reached Texas beaches.⁶² Loss of the more volatile and soluble components through extensive weathering of the oil during travel time to Texas waters decreased the potential for detrimental impacts since these components are generally more toxic. Impacts on Mexican resources are incompletely known due to limited study and availability of results from such investigations as were conducted.

Reports indicate that few shrimp in Mexican and U.S. waters were tainted by settling oil debris. Along Padre Island, Texas, the percentage of total birds with any signs of oil on their feet or plumage never exceeded 10 percent; 82 birds were found with up to 75 percent of their bodies covered with oil and judged unlikely to survive.⁶³ Studies found decreasing populations of benthic fauna following the incident, but these circumstances could not be conclusively linked to the Ixtoc accident since minimal deposits of hydrocarbons were found in associated sediments.⁶⁴ No reports of long-term impacts on resources in U.S. or Mexican waters have been identified.

Most of the impact to the Texas beaches occurred between August and mid-September 1979. During this time business in the recreational and tourist

⁶¹ National Research Council. *Using Oil Spill Dispersants on the Sea*. National Academy Press, Washington, D.C., 1989, p. 320.

⁶² Bedinger, C. A., Jr., and C. P. Nulton. *Analysis of Environmental and Tar Samples from the Nearshore South Texas Area after Oiling from the Ixtoc I Blowout*. *Bulletin of Environmental Contamination and Toxicology*, v. 28, no. 2, Feb. 1982, p. 166.

⁶³ Chapman, Brian R. *Effects of the Ixtoc I Oil Spill on Texas Shorebird Populations*. In *Proceedings, 1981 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 461-465.

⁶⁴ Boehm, Paul. *Ixtoc Oil Spill Assessment: Executive Summary*. Energy Resources Co., Inc., Cambridge, Mass., Apr. 1982, p. 22-24. NTIS PB82-197773.

industries in the South Padre Island area dropped significantly.⁶⁶ Dispersants were not used by the United States. By the end of 1980, the only known remnants of oil from Ixtoc I were scattered patches of tar mats along the Texas barrier island beaches.⁶⁶ Because of the numerous natural seeps in the area similar patches appear every year, but they were more numerous and extensive in 1980, and analysis showed that some originated at Ixtoc.

Cleanup costs on the Texas beaches exceeded \$4 million. The estimated total cost of capping the well and containing the environmental damage, including lost oil revenues, amounted to \$219 million.

Burmah Agate

On November 1, 1979, a collision of the Liberian-registered tanker, *Burmah Agate*, and the Liberian-registered freighter, *Mimosa*, produced the largest oil spill in U.S. waters up to that time. The accident occurred off the coast of Texas about five miles southeast of the Galveston Entrance Channel. The *Burmah Agate* was loaded with 397,800 barrels of Nigerian crude oil. The collision ruptured the starboard midship tanks resulting in a fire and explosions that left 33 dead. The ship settled on the bottom in 44 feet of water with its deck awash. Eventually, 24 of the 36 tanks were ruptured, releasing about 250,000 barrels of oil, much of which was consumed in the fire that continued to burn out of control for over two months. Over 150,000 barrels of oil were eventually salvaged from the forward tanks before the ship was refloated and towed to Brownsville, Texas for scrap. Another 6,700 barrels of oil/water emulsion were recovered from the water. Because of the predominance of offshore winds during the first month of the spill, most of the oil not consumed by the fire was dispersed offshore. Of the approximately 62,000 barrels of oil that were released and not burned, 2,100 eventually reached shore.

Beach impacts directly attributable to the spill occurred as far as 290 miles from the wreck. Prevailing winds and currents moved the oil toward the southwest. The first oil came ashore 155 miles southwest of the wreck. The heaviest oiling occurred between November 19 and 21 when up to 1,500 barrels beached along the western half of Galveston Island. Cleanup was initially by manual labor and front-end loaders. Eventually, the primary

⁶⁶ U.S. Congress. House. Committee on Merchant Marine and Fisheries and Committee on Public Works and Transportation, Subcommittee on Water Resources. Blowout of the Mexican Oil Well Ixtoc I. Hearings, 96th Cong., 1st Sess., Corpus Christi, Texas, Sept. 8 and 9, 1979, p. 108-118.

⁶⁶ Gundlach, E. R., K. J. Finkelstein, and J. L. Sadd. Impact and Persistence of Ixtoc I Oil on the South Texas Coast. In Proceedings, 1981 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 477-485.

method of beach cleanup involved pooling the oil by hand and picking it up with vacuum trucks. The latter method considerably reduced the amount of sand removed from the beach. By the end of the spill, a total of 1,500 cubic meters of oiled sand and 1,930 barrels of oil, water, and sand mixture were recovered from the beaches. Coastal processes aided the rapid recovery of Galveston beaches.⁶⁷

The only known marsh impact occurred when approximately 5 barrels of oil coated about 1300 feet of marsh fringing Smith Point in Galveston Bay. Because of the relatively small area affected, no cleanup was attempted. It was thought that any human disturbance to the marsh area might be more detrimental than the relatively limited amount of oil. Over \$850,000 was spent on onshore cleanup efforts. Offshore impacts were not reported.

Alvenus

On July 30, 1984, the British-registered tanker, *Alvenus*, grounded in the Calcasieu River Channel entrance about 11 miles south-southwest of Cameron, Louisiana. The vessel's hull buckled and fractured vertically on both sides and across the cargo tank tops discharging approximately 65,500 barrels of Venezuelan crude oil over a 6-day period. The grounding was later attributed to a combination of vessel squat and isolated channel shoaling. Attempts to contain and recover the oil at sea were ineffective because of rough seas and lack of adequate equipment for the magnitude of the spill.

Precautions were taken to prevent the outbreak of fire by continuously pumping inert gas into the ruptured cargo tanks. Decks were also covered with foam, and electrical power in the damaged area was shut off. Oil continued to flow from both sides of the ship. A major concern was the numerous aircraft employed by the news media, which at times flew within 50 feet of the stricken vessel, prompting the Coast Guard to request the Federal Aviation Administration to impose a restricted airspace over the vessel.⁶⁸ Approximately 284,000 barrels of crude oil remained onboard the *Alvenus* and were salvaged.

The spilled oil formed a 75-mile-long slick that traveled west from the wreck for over 100 miles, arriving on Texas beaches on August 3 and 4 along

⁶⁷ Thebeau, Larry C. and Timothy W. Kana. Onshore Impacts and Cleanup During the *Burmah Agate* Oil Spill--November 1979. In Proceedings, 1981 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 144.

⁶⁸ Alejandro, Anthony C. and Jack L. Buri. *M/V Alvenus: Anatomy of a Major Oil Spill*. In Proceedings, 1987 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4452, 1987, p. 27.

the west end of Galveston Island. Cleanup crews encountered a major problem when a large portion of the slick approached the shoreline, absorbed suspended solid particles, and sank in the nearshore surf zones. The oil became trapped between sand bars not more than 100 feet from shore, in water too deep for heavy land-based equipment and too shallow for floating recovery equipment. Cleanup crews had to wait until the oil beached, a process that took several weeks. The continued re-oiling of the beach required repeated recleaning of the beach area.

An effort was made to minimize the amount of sand removed from the beaches. Sand contaminated with an oil concentration greater than 10 percent (heavily oiled) was classified as waste and removed from the entire beach area. Moderately contaminated sand was relocated and spread in the back beach area adjacent to existing sand dunes. Lightly oiled sand was spread in the non-tidal, mid beach area. Analyses of the oil-contaminated sand indicated that the weathered oil contained no toxic components and that water-soluble fractions were no longer present, thus minimizing further leaching. There was no evidence of leaching from the oiled sand that was spread on the beaches above the tidal zone.

During the beach cleanup, conflict arose over who owned the contaminated beach sand. The State wanted the sand removed from the beach front while the land owners wanted it either left where it was or moved to the dune line seaward of the vegetation line. The amount of sand eventually removed from the beaches was roughly equivalent to the amount that would be removed by a small winter storm.

The Federal Scientific Support Group debated the merits of mechanical cleaning, which might kill organisms that survived smothering, versus letting the oil remain. From the onset of the spill, there were extensive discussions regarding the feasibility of dispersing the viscous Venezuela crude oil and the potential environmental damage, but dispersants were not used. It was concluded that available dispersants would not have significantly reduced the surface area of the spill, altered the location of the shoreline impact, or reduced the net damage to natural resources. Despite mechanical cleanup, the economic damage was great since the Galveston's resort beaches were heavily oiled during the height of the tourist season.

Booms prevented any significant quantity of oil from entering the inland hatchery environments of East Bay, Galveston Bay or West Bay. No significant lasting environmental damage was documented as a result of the *Alvenus* oil spill.⁶⁰ The oil was known to have a smothering effect on some marine organisms in the area; however, the Scientific Support Group determined that the affected organisms were a minor loss to the local ecosystem which soon recovered. Other than algae growing on rocks, most of the organisms in the area are transient and able to move to a more suitable

⁶⁰ Ibid., p. 31.

habitat. Several dead crabs, fish, and rays were found but these mortalities could not be directly attributed to the oil spill. The crabs, for example, were mostly female and may have expired normally after spawning.⁶⁰ Throughout the beach-cleaning period, fishing and shrimping activities continued offshore.

By mid-November, algae were again growing on rocks and groins and even growing over some oil that remained. Also, indigenous grasses were growing through the oiled sand in back beach areas.

Amoco Cadiz

On March 16, 1978, the Liberian-registered tanker, *Amoco Cadiz* grounded and broke up off the coast of Brittany, France and, over the next 15 days, spilled her entire cargo of 1,635,000 barrels of light Arabian crude oil. At the time of its occurrence, this was the largest oil spill the marine environment had experienced (and is over 6 times the size of the *Exxon Valdez* spill). The tanker suffered steering failure 8 miles north of the Ile d'Ouessant in the English Channel, and grounded on rocks at high tide within sight of shore. As the tide ebbed, the ship broke in two.

Approximately 90 percent of the cargo was lost in the first 11 days, during which time the winds averaged between 20 and 30 knots. The strong winds precluded most efforts at removing oil from the sea and soon drove the oil ashore along 250 miles of the French coast. The oil came ashore over a 4-week period, resulting in an almost continual oiling of the coastline. Less than 146,000 barrels were eventually recovered, most from beach and shoreline areas. A considerable portion of the oil that came ashore, and was not removed manually in the massive cleanup effort, eventually became buried in the sediments or entrapped in the low-energy salt marshes and estuaries. Efforts were made to remove oiled vegetation and sediments in some marsh areas with the expectation that recovery would be more rapid on clean subsurface sediments.

Attempts to combat the oil at sea included the use of about 3,000 tons of dispersant and some chalk, used as a sinking agent. Dispersant use was permitted only in water depths greater than 50 meters (164 feet) and only where no major marine resource would be endangered. Dispersants appeared to be used effectively in some instances and ineffectively in others. Effective use was limited by the broad aerial distribution of oil along the coast, the patchiness of the oil in windrows, and limited favorable weather conditions. The use of chalk as a sinking agent did not appear to be very effective and

⁶⁰ Ibid., p. 32.

was objectionable on environmental grounds because of the smothering effect on bottom-dwelling organisms.⁶¹

While at sea, the oil underwent extensive evaporation and biodegradation so that the petroleum that stranded had changed in character from the original cargo. All of the oil that came ashore was in the form of some type of oil-water emulsion or "mousse," with the oil content ranging from 8 percent to 48 percent.

Of the 455,000 barrels of oil estimated to be on the shore at the end of March 1978, 67,500 barrels were estimated to be remaining one month later. The reduction was due to cleanup activities and the extensive biodegradation of the stranded oil. The affected shoreline areas included rocky coasts, recreational beaches, tidal estuaries, and coastal marshes. Figure 3 is a quantitative estimate of the disposition of the oil during the first month of the spill.

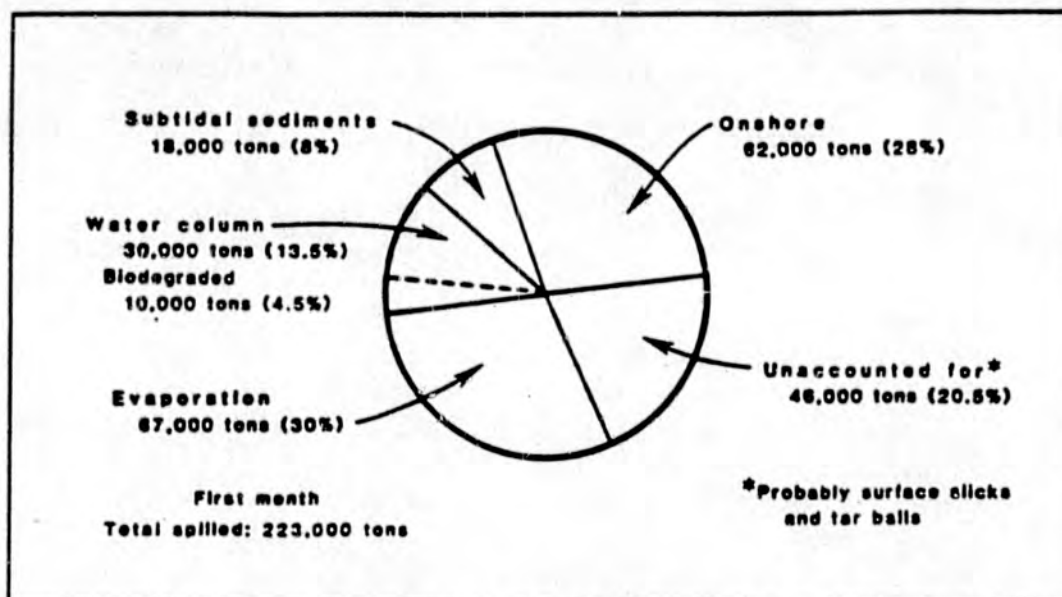


Figure 3. Distribution of *Amoco Cadiz* oil during the first month of the spill. Source: *Science*, July 8, 1983.

Since much of the coastline in the affected area is a resort area known for its beautiful pink granite, the cleaning of rocks, retaining walls, ramps, and boulders was considered of high priority for safety, aesthetic, and economic reasons. Most of this effort was accomplished through flushing with water and water-detergent mixtures under high pressure. Both hot and cold

⁶¹ Hann, Roy W., Jr. Unit Operations, Unit Processes and Level of Resource Requirements for the Cleanup of the Oil Spill From the Supertanker *Amoco Cadiz*. In Proceedings, 1979 Oil Spill Conference, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4308, 1979, p. 154.

water were used, and, upon completion, the rock walls, ramps, and boulders appeared relatively clean. Sand blasting was tested, but was not recommended because of the high cost. The cleanup effort lasted several months, although some restoration activities extended into 1979 and beyond.

Because of its magnitude and impact on a range of coastal areas, including marshes in particular, the spill has been the subject of extensive ecological investigations. An initial three-year study of the effects of the spill was sponsored by Amoco Transport Company and conducted under the joint efforts of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the French Centre National Pour l'Exploitation Des Océans (CNEXO).⁶² These studies were subsequently followed by several others. Figure 4 is a synthesis of data indicating the relative persistence of *Amoco Cadiz* oil in various environments over the first three years. Fate and effects studies were severely complicated, however, when on March 7, 1980 the tanker *Tanio* broke up 40 miles off the Brittany coast releasing over 50,000 barrels of oil into many of the same areas affected by the *Amoco Cadiz* spill.

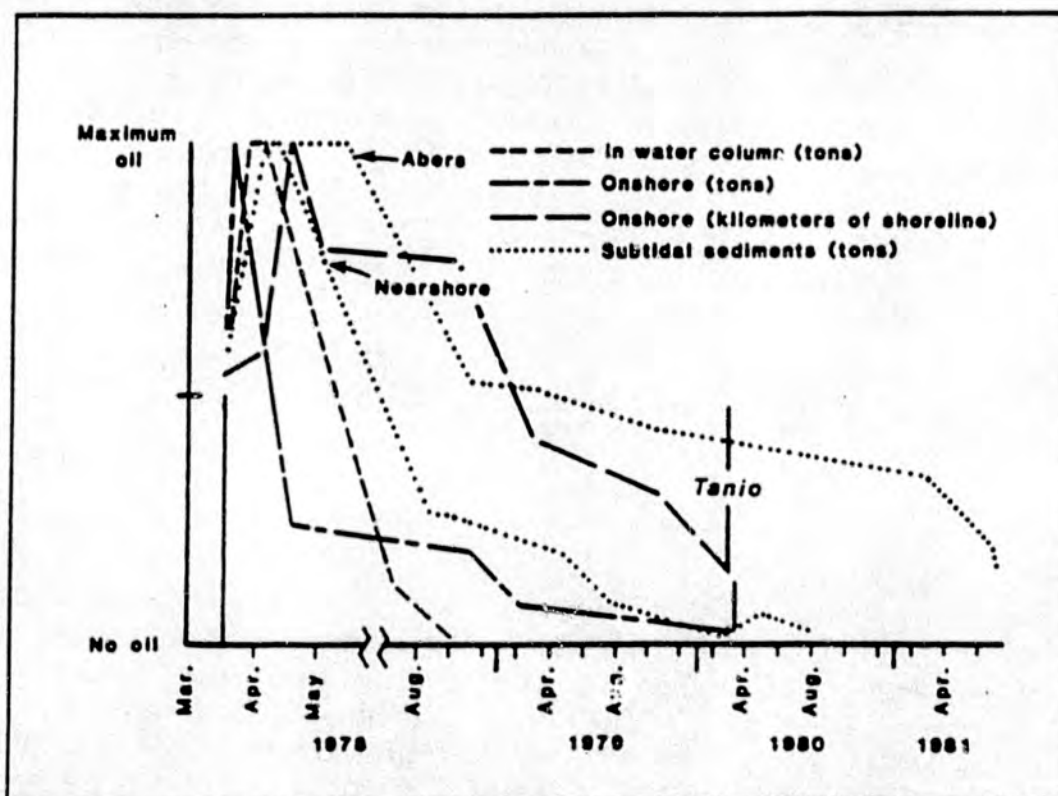


Figure 4. Relative persistence of *Amoco Cadiz* oil in various components, March 1978 through June 1981.

Source: *Science*, July 8, 1983.

⁶² Ecological Study of the *Amoco Cadiz* Oil Spill. Report of the NOAA-CNEXO Joint Scientific Commission, Oct. 1982, 419 p.

The *Amoco Cadiz* spill affected the most exposed sites, such as rocky shores, the least. A variety of intertidal rocky shore animals were killed, but in general, rocky shores suffered little damage except where they were damaged from cleanup operations.⁶³ Sandy shores retained oil as buried layers for several years, but dead animals were found only immediately after the spill. Exposed intertidal mudflats had almost their entire fauna killed by oil from the water column until recolonization could occur. Decreases in biomass of phytoplankton were observed for several weeks in the immediate vicinity of the wreck and in the highly contaminated tidal rivers. In contrast, further from the wreck phytoplankton production was elevated, perhaps stimulated by either low levels of petroleum hydrocarbons or nutrient release from dead organisms.⁶⁴ Over 4,500 oiled birds were recovered dead, presumably from physical effects of the oil. A disastrous effect on the bird population had been feared, but it did not materialize, suggesting that the survival potential of seabirds, at least for the eastern North Atlantic populations, is quite good.⁶⁵ There was some mortality of fish in the vicinity of the wreck and some bottom-dwelling species showed evidence of fin rot with the percentage of individuals affected diminishing from 80 percent after 9 months to 10 percent after 20 months. However, it was also found by comparison to control areas, that the area oiled by the *Amoco Cadiz* spill was clearly not pristine before the spill.⁶⁶ For example, investigators found that 21 months after the oil spill, hydrocarbons (not all derived from the spill) were only one of three factors (the others were silver and mercury) associated with adverse effects on oyster populations in the area.⁶⁷ Although hydrocarbons from the spill were still found in oysters up to 27 months after the spill, there was little evidence of histopathological and biochemical damage.⁶⁸ At the same time, evidence of

⁶³ National Research Council, *Oil in the Sea: Inputs, Fates, and Effects*, p. 561-566.

⁶⁴ *Ibid.*, p. 564.

⁶⁵ *Ibid.*, p. 574.

⁶⁶ Gilfillan, Edward S., David S. Page, Barbara Griffin, Sherry A. Hanson, and Judith C. Foster. *The Importance of Using Appropriate Experimental Designs in Oil Spill Impact Studies: An Example From the Amoco Cadiz Oil Spill Impact Zone*. In *Proceedings, 1987 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4452, 1987, p. 503.

⁶⁷ *Ibid.*, p. 507.

⁶⁸ Neff, J. M. and W. E. Haensly. *Long-term Impact of Amoco Cadiz crude oil on oysters *Crassostrea gigas* and plaice *Pleuronectes platessa* from Aber Benoit and Aber Wrac'h, Brittany, France*. In *Ecological Study of the Amoco Cadiz Oil Spill*. Report of the NOAA-CNEXO Joint Scientific Commission, October 1982, p. 269-327.

damage continued to be found in plaice (bottom-dwelling fish) in areas heavily affected by the spill, although substantial improvement was noted during that period.

Two years after the spill it was reported that there was no recovery at the most heavily oiled marsh areas. This led to predictions that several decades may be required for a return to prespill conditions by natural processes.⁶⁹ Others who studied the spill in the first 2 years suggested that if the oiled marshes were left untouched, spontaneous recovery may require centuries and recommended mass planting of marsh vegetation.⁷⁰ However, on the basis of further studies, it now appears that marshes that were oiled but had no cleanup were essentially restored by natural processes within 5 years, whereas in cleaned marsh areas, restoration took 7 to 8 years.⁷¹ Marshes that had been subjected to extensive cleanup efforts experienced increased erosion of fine sediments and despite extensive artificial plantings, their restoration was delayed by 2 to 3 years. In Aber Benoit, an estuary heavily affected by the spill, the only measurable residues of weathered petroleum remaining after 8 years were found in isolated soft sediment locations that served as repositories for fine sediment from other parts of the estuary.⁷²

In the months following the spill, journalists and individuals associated with affected localities and industries made numerous assertions about the extent of lost earnings in the fishing and tourist industries, and the extent of cleanup and restoration costs, property damage, and other effects. "Brittany will look like a desert" was one oft-repeated phrase. The magnitudes of the short-run and long-run physical, biological, and monetary damages as a result

⁶⁹ National Research Council, *Oil in the Sea: Inputs, Fates, and Effects*, p. 566.

⁷⁰ Vandermeulen, J. H., B. F. N. Long, and L. D'Ozouville. *Geomorphological Alteration of a Heavily Oiled Saltmarsh (Ile Grande, France) as a Result of Massive Cleanup*. In *Proceedings, 1981 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4334, 1981, p. 350.

⁷¹ Baca, Bart J., Thomas E. Lankford, and Erich R. Gundlach. *Recovery of Brittany Coastal Marshes in the Eight Years Following the Amoco Cadiz Incident*. In *Proceedings, 1987 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4452, 1987, p. 459-464.

⁷² Page, David S., Judith C. Foster, Paulette M. Fickett, and Edward S. Gilfillan. *Long-term Weathering of Amoco Cadiz Oil in Soft Intertidal Sediments*. In *Proceedings, 1989 Oil Spill Conference*, sponsored by EPA, USCG, and API, American Petroleum Institute publication 4479, 1989, p. 401-405.

of the spill became questions of national and international focus and interest. Thus, the social costs of this oil spill were also well studied. The total economic costs to the world were estimated to range from about \$190 million to \$290 million (1978 dollars).⁷³ The largest components of the total cost were cleanup expenditures, losses to the oyster-culturing industry, and the loss of the tanker and cargo. The loss of recreational values were estimated to range from about \$1.5 million to over \$80 million depending on the unit values of losses assumed. The French Government and others originally sought \$2 billion in damages, but Amoco's liability was considerably reduced because the judge found relatively little long-term ecological damage and recommended an award of \$115.2 million.⁷⁴

CONCLUSIONS

Since the first well was drilled over 130 years ago, petroleum has become society's major energy source. Petroleum and petroleum products have played a significant role in the progress of civilization. Materials made from petroleum are virtually everywhere. Petroleum production has been among the least damaging to the environment of any of the extractive earth resources industries. Yet no technology is without environmental cost and none is fail-safe.

An oil spill can be a devastating occurrence. However, past spills have not been long-lived events. For the most part, the longest residence time that spilled oil appears to have had in the marine and coastal environment was generally less than a decade--often much less. The major ecological impact has come at the time of the spill or within the first few months. Beyond a few months, most oil has been reduced to tarry residues or was chemically detectable in sediments and resident organisms, which may be of scientific interest, but in terms of further ecological impact, has proved to be fairly insignificant overall. Public impressions of socioeconomic and environmental damage that occurred and concerns over further ecological impacts have lasted much longer. The life span of the media coverage has been shorter than the major ecological impact of the spill, but probably of greater significance. With the possible exception of special environments, predictions of long-term effects have been largely unsubstantiated. Based on the evidence available, there has been no evident irrevocable damage to marine resources on a broad scale to justify serious allegations of unknown, but significant, long-term effects.

The short-term impact of a major spill can be devastating to the organisms in the immediate vicinity, including shellfish, finfish, marine

⁷³ U.S. Department of Commerce, National Oceanic and Atmospheric Administration. *Assessing the Social Costs of Oil Spills: The Amoco Cadiz Case Study*. July 1983, 144 p.

⁷⁴ Wall Street Journal, Mar. 28, 1989, p. A13.

mammals and waterfowl. Experience, thus far, however, would indicate that this has not made a noticeable impact on world population levels of any species. For species of shellfish, finfish, and waterfowl that are harvested, the mortality from an oil spill, so far as is known, has never come close to approaching the magnitude of the annual harvests.⁷⁶ Recolonization of an area temporarily polluted from oil appears to be rapid for most species.

A major short-term impact of a major spill is the visual impact created by an oiled shoreline and featured by the media coverage of the event. The media coverage typically includes heartrending scenes of oiled or dead birds and sea life, and oiled beaches. The portrayal is generally one of a major catastrophe.⁷⁶ While not minimizing the effect of an oil spill, it appears that the environmental damage has been less than one would surmise from immediate visual appearances or media coverage.

Nearly one year after the grounding of the *Exxon Valdez* the city of Valdez issued a press release appealing to the world's press "to avoid repeating errors and myths" in covering the spill anniversary. The press release noted that the loss of wildlife was a small fraction of existing populations in the sound and that most of the affected shoreline is remote and outside the area likely to be seen by seaborne tourists. On the other hand, the Alaska Coalition, an environmental group, marked the anniversary by calling on Congress to establish a memorial for the wildlife lost in the accident by declaring the entire Arctic National Wildlife Refuge a wilderness area.

Based on the record of past spill events, it would also appear that beyond a moderate human effort to clean up an oil spill, nature does a much better job than humans. In fact, in some instances, it would appear that massive physical cleanup efforts delayed the natural ecological restoration of the affected area although the appearance, particularly of rock and beach areas, may be improved sooner. This might raise the question of whether the cost to society of massive physical cleanup efforts is equal to the social and environmental benefit. In the case of the *Exxon Valdez* spill, the cost of cleanup to date has exceeded \$2 billion (far more than has been expended on any previous spill), where most of the affected shoreline is "remote and outside the area likely to be seen by seaborne tourists." The unfortunate spill in Prince William Sound will, however, offer an opportunity to study the effects of a large oil spill in a subarctic environment. Whether the effects of the *Exxon Valdez* spill will match the experiences of spills in more temperate environments remains to be seen.

⁷⁶ For example, about 300,000 waterfowl are taken each year during hunting season on Maryland's "eastern shore" alone.

⁷⁶ Yen, Marianne. Judge Sets \$500,000 Bail for Disaster Unequaled 'Since Hiroshima'. Washington Post, Apr. 6, 1989, p. A1, A11.

Oil spills are not new events and many have been studied. Obviously, all of the possible physical oceanographic, socioeconomic, and environmental effects of an oil spill are not known, and further scientific study will be of value. On the other hand, from a public policy perspective, the major socioeconomic and environmental impacts of an oil spill are reasonably well known, and, on the basis of that knowledge, the major effects of a future spill should be fairly predictable.

Public policy decisions have to balance the overall needs and benefits to society of a particular action versus its costs and risk. For example, public policy decisions, such as whether to permit offshore drilling in a particular area, are properly based in part on a scientific assessment of the probability of spills from offshore production versus imported oil and the severity of the consequences. The experience of the past 50 years and the careful research of marine scientists now provide the basis for realistic estimates.

EPILOGUE

The oceans are ancient and throughout the course of time many sea-dwelling species have flourished and faded while new species have evolved. Now, for the first time, there is broad human concern for the well-being of the seas because, as no other creature before, human beings have the ability to alter a wide range of marine ecosystems dangerously and quickly. In the pursuit of food and living resources, humans have even threatened the survival and caused the extinction of many species. Fortunately, however, the oceanic environment is not fragile;⁷⁷ in fact, it is extraordinarily resilient. It has evolved through ice ages, global warming, bombardments of cosmic radiation, fluctuations of the sun, massive volcanic eruptions, and collisions of comets and meteors. Mass extinctions of species were associated with some of these events, but life forms continued to adapt, evolve, become more complex, and flourish.

Many physical and biological processes in the marine and coastal environment are only poorly understood. For these reasons, it is particularly difficult for scientists to measure the full impact of an oil spill and sometimes the results appear contradictory. To date, pollution from offshore petroleum activities has not appeared to be a significant threat to the survival of the various species. Nor is it, if compared to other activities and possible pollutants, likely to be ranked as a leading threat in this regard. Despite short-term media attention to the catastrophic nature of major spill events, the chemicals contained in petroleum have long been part of the marine environment and physical impacts are likely to be temporary in the dynamic natural flux of the coastal environment.

⁷⁷ Fragile and environment are commonly linked together in media accounts of spill events.

MARINE OPERATIONS AND LOGISTICS DURING THE EXXON VALDEZ SPILL CLEANUP

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ABSTRACT: The Exxon Valdez oil spill required unprecedented marine operations and logistics support for cleanup. At the peak of operations, more than 11,000 people, 1,400 vessels and 85 aircraft were required.

Due to the remoteness of the spill location and the absence of land access, virtually all cleanup was conducted from vessels. Three types of vessels were used: landing craft and barges for oil recovery and shoreline treatment; berthing vessels for housing offshore workers; and support vessels for transporting personnel and materials.

Major logistic challenges in the oil spill response included providing offshore housing; replenishing food, water, and fuel for the offshore operations; establishing a large aircraft operation; installing a telecommunications network that was essentially built from scratch; providing onshore support; handling and disposing of more than 25,000 tons of oily solid waste and several hundred thousand barrels of oily liquid waste; and safely demobilizing the effort.

The March 24, 1989 grounding of the tank vessel *Exxon Valdez* on Bligh Reef resulted in an oil spill of approximately 258,000 barrels that began in Prince William Sound and later impacted portions of the southern Alaska shorelines in the Gulf of Alaska, as shown in Figure 1. The resulting cleanup operations were spread over an area more than 500 miles long, although less than 15 percent of the shoreline in this area was impacted by the oil spill. The areas impacted were remote in that virtually all of them required access by water or air, few could be served by existing communications, little housing was available, and the entire operation was distant from most sources of cleanup equipment and materials.

The remoteness combined with the magnitude of the task and limited weather window in which to conduct the work resulted in very high marine operations and logistics requirements. At the peak of operations, more than 11,000 personnel, 1,400 vessels, and 85 aircraft were working on the cleanup. Figure 2 shows the personnel buildup and illustrates the high support requirements of the operations. Of the more than 11,000 total personnel, about 3,400 worked on shoreline treatment and the remaining were onshore and offshore. Figure 3 shows the buildup of vessels. In order to utilize all available vessels in the response and to quickly mobilize and construct specialized vessels, it was necessary to obtain a number of waivers from normal Coast Guard requirements.

Overall operations were coordinated out of the Valdez Command Center and were geographically divided into Prince William Sound (PWS) and Gulf of Alaska (GOA) areas. PWS operations were also

coordinated from Valdez while GOA operations were coordinated out of satellite command centers in Seward, Homer, and Kodiak (Figure 1).

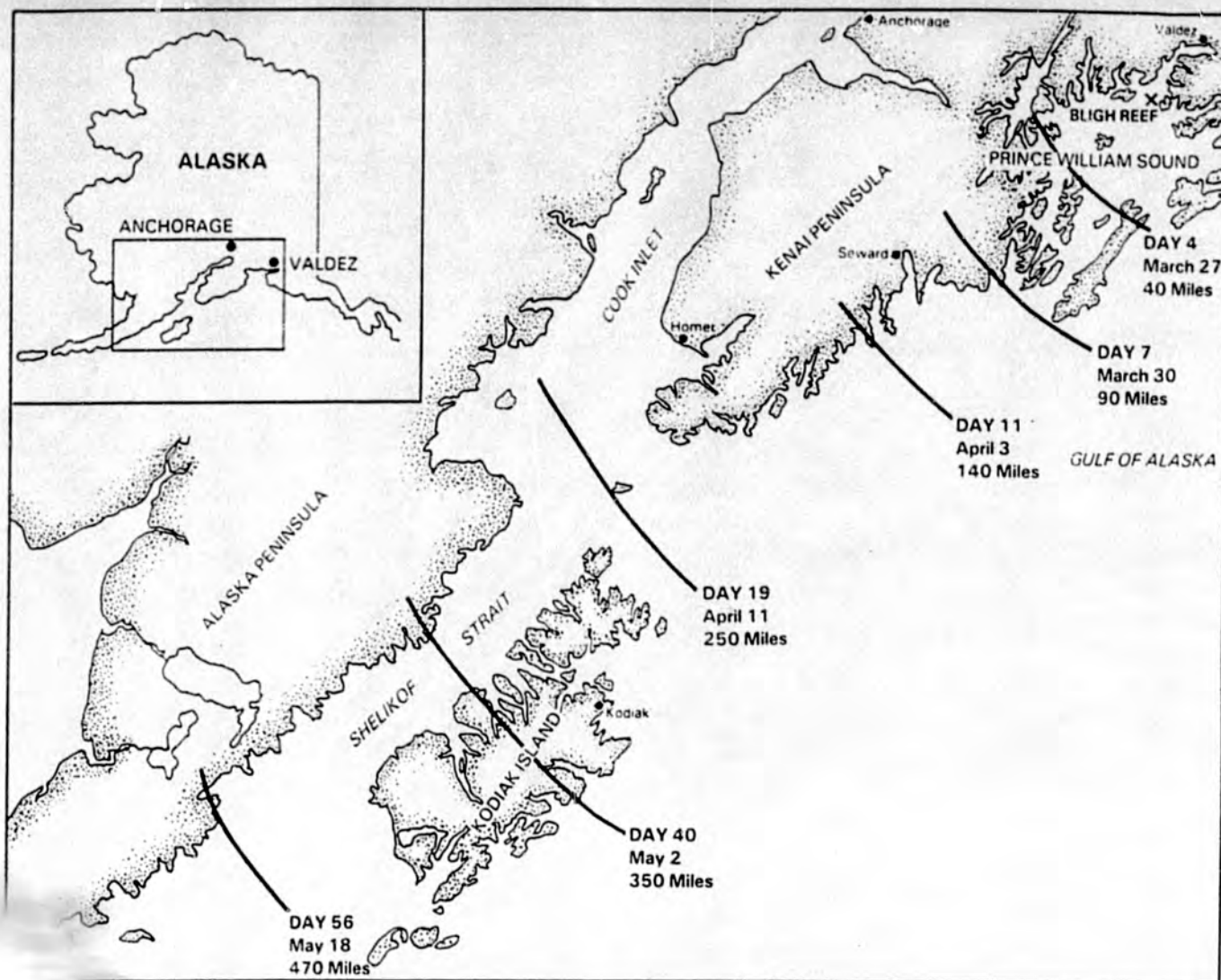
From the onset, safety was a major priority. The first formal safety training was performed on day nine of the cleanup effort. The cleanup methods changed throughout the effort and the safety programs changed in concert. In spite of the massive personnel buildup and inherently difficult working conditions, the safety program showed continual improvement and the total number of lost time incidents averaged 34 percent less than heavy construction over the same period (Figure 4).

This paper describes the approach to the cleanup of the remoteness factors so that the necessary personnel and equipment could be mobilized and supported to effect the cleanup. It also describes the 1989 oil spill response. Since the spill occurred in the areas of largest impacts occurred there and the cleanup was concentrated in these areas, personnel and equipment were concentrated in these areas. Of the 7,000 total offshore workers were in the PWS area. These were generally similar to PWS but on a lesser scale. The 1989-90 Winter Operations and 1990 activities are not included in this report.

PWS marine operations and logistics

Six large task forces were assembled for Prince William Sound operations, with each composed of about 400 to 700 people and 70 to 100 vessels. As shown in Figure 5, approximately one-half were direct cleanup personnel, either oil spill response technicians (OSRTs) or treatment vessel crews, and the remaining were support personnel. Common logistics vessels, animal rescue operations and other support also required more than 1,000 offshore people. The vessels in a typical task force included barges, landing craft, skimmers, cruisers, skiffs, and numerous fishing boats such as bowpickers, seiners, and tenders. Their functions are shown in Table 1. Task Force 2's support complex, consisting of a berthing barge, supply barge, shower/wash barge, and associated operations and support vessels is shown in Figure 6. In addition to the task forces, a number of vessels and personnel provided common support to all task forces and smaller units.

Berthing vessels. All of the shoreline cleanup and offshore support personnel had to be housed on the water. To meet the large requirements, several different types of vessels were used. At first, fishing boats and other readily available marine craft were used. These small vessels continued to be used for smaller teams after larger units were available.

Figure 1. Chronology of oil movement from the *Exxon Valdez*

excursion boats and fish processing ships were the fastest way to obtain larger numbers of berths, but they were still a limited source. Navy transport ships quickly provided a larger number of berths but the quarters were cramped for extended operations. The majority of the long-term berths were provided by camps on eleven conventional

deck barges. The camp housing was installed on the barges in shipyards, where plumbing and electrical work was also done. Because berthing barges were considered facilities and not vessels, they were subject to largely the same food service, fresh water and wastewater permitting requirements as permanent onshore commercial facilities.

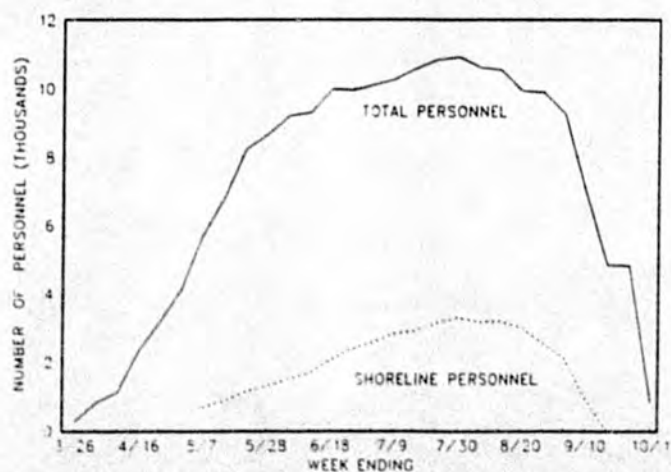


Figure 2. Number of shoreline and total personnel for oil spill response

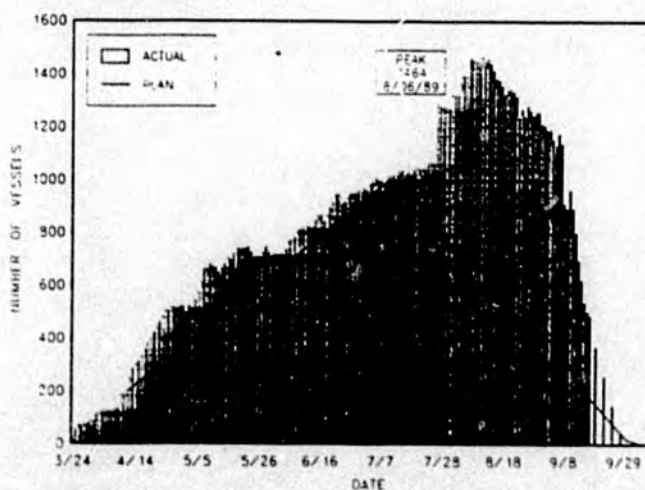


Figure 3. Number of vessels utilized in oil spill response

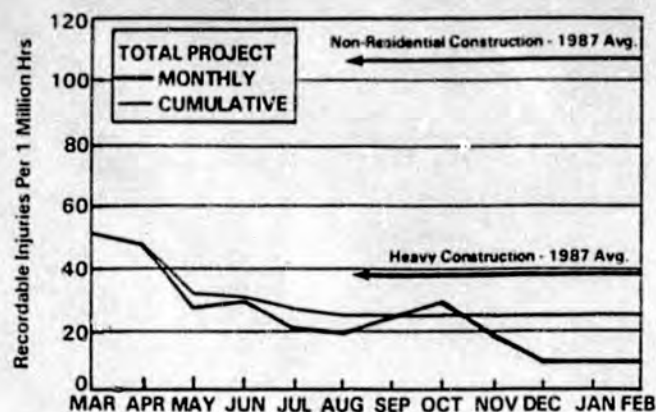


Figure 4. Safety performance during oil spill response

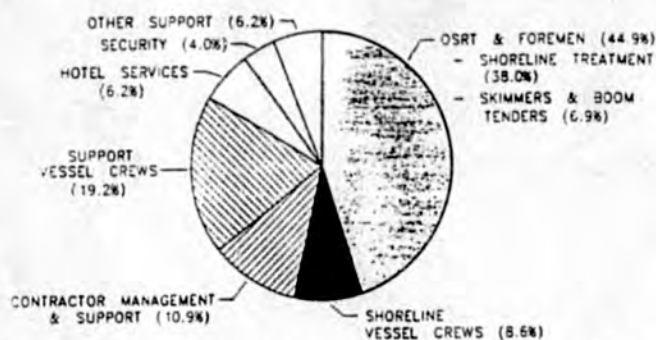


Figure 5. Functions of task force personnel (excluding Exxon and Crawford)

A self-contained semi-submersible derrick barge was able to provide the largest number of berths in a single vessel. Table 2 compares the key characteristics of the major berthing vessel types.

The berthing vessels and other barges were moored in sheltered bays and coves within Prince William Sound to reduce their exposure to extreme weather conditions. Local fishermen were consulted as to the best sites for the moorings based on their knowledge of winds, seas, and underwater hazards. All mooring systems were designed as single point moorings (SPM) with a design basis of 50 knot winds and ten-foot seas. A tug was assigned to each barge or cluster of barges to assist in the event of a storm in excess of the design conditions.

Crew transfer vessels. A large number of vessels were needed for crew transfers between the command center cities, berthing vessels, production and support vessels, and the shoreline work sites. The

Table 1. Typical task force vessels,

Logistics vessels	
Berthing vessels	3
Crew transfer	18
Storage/supply	11
Waste handling	8
Safety/medical	4
Other	9
	53
Cleanup vessels	
Shoreline treatment	17
Boom tending	14
Crew transfer	20
	51

1. Numbers reflect the average composition of the fleet. Vessel types and numbers varied from task force to task force and from day to day.



Figure 6. Task Force 2 support complex

Table 2. Berthing vessels

Vessel type	Beds	Days to outfit	Comments
Excursion boats	25-100	4-9	Quickly mobilized, limited mooring systems, require support barge with gear washing, potable water, and sewage handling
Fish processors	50-200	2-5	Largely self-sufficient, good propulsion and mooring systems
Navy ships	500	1-2	Quickly mobilized, large capacity but cramped berthing, good propulsion and mooring, require support barge with gear washing and sewage storage
Camp barges	50-250	7-29	Slower mobilization, large capacity, no mooring systems, require support barge, most weather sensitive
Derrick barge	548	1-2	Large capacity, slow mobilization, existing mooring system but lengthy installation, self-sufficient

majority of these were 24- to 40-ft fishing boats, although they varied from small inflatables to large ocean-going crew boats. Many functioned in multiple roles such as tending boom, transporting supplies, and transferring trash.

Shoreline treatment vessels. At the peak, 87 vessels were outfitted with equipment for treating the shorelines: 61 landing craft and 26 barges. Construction was performed in Valdez, Seattle, and Ketchikan. A number of skimmers and small pontoon barges were also used. The primary types were:

- Miri-vessels.** The 61 landing craft equipped with both cold and hot water washing equipment were referred to as mini production vessels. These were the smallest shoreline treatment vessels, and their self propulsion, shallow draft, and bow ramps facilitated their ability to maneuver and access shorelines. Many were readily available in Alaska, and they could be mobilized the soonest; outfitting time was less than one day. About 40 percent came from military sources.

- Maxi-barges.** Conventional barges outfitted to provide larger quantities of heated water were called maxi-barges. The time to outfit these barges was typically 6 days. The maxi-barges varied in length from 128 to 180 feet, and in width from 33 to 54 feet. Their higher freeboards and deeper drafts, combined with the need for a tug to maneuver them, made the Maxis best suited for treating longer sections of impacted shorelines.

- Omni-barges.** The omni-barges were equipped with industrial heaters and an articulating arm to allow delivering heated water to hard-to-reach areas. They were 115 feet to 140 feet long and about 40 feet wide, with drafts of 2.5 to 4 feet. All but one were self-propelled and constructed of interlocking sectional barge components as shown in Figure 7. The Omnis required five to seven days for assembly. An

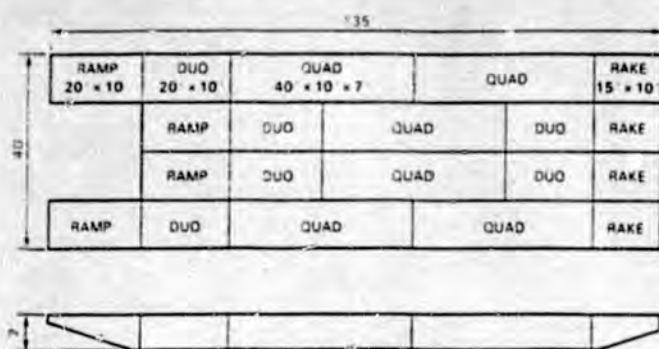


Figure 7. Interlocking float pattern for one Omni-barge configuration

additional 4-5 days were required to install the shoreline cleanup equipment.

• Bioremediation vessels. To apply the liquid fertilizer used in the shoreline bioremediation process later in the cleanup, water washing equipment was removed from six cold water mini vessels, and bioremediation application tanks and sprayers were installed. To access shallow areas that the minis couldn't reach, small pontoon vessels were similarly outfitted.

Resupply in Prince William Sound. At the peak of offshore operations, the six task forces required about 100,000 gallons of fuel, 30 tons of food, 150,000 gallons of fresh water, and 18 tons of materials on a daily basis. Additional supplies were required for the vessels and personnel providing common offshore logistic support and government agency operations. Even larger quantities of waste were hauled back daily.

To expedite the fueling of vessels and helicopters, two fuel depots were set up in Prince William Sound. Motor gasoline, aviation gasoline, jet fuel, diesel fuel, lube oil, and hydraulic oil were available. Food, water, and materials were delivered on ocean-going workboats on a regular schedule to each task force. In addition, smaller boats delivered fresh groceries and specialty items on an as-needed basis. Later, fresh water sources were developed in PWS to reduce logistical needs.

Other support vessels. Barges were particularly important in meeting the various marine support needs. Due to limited availability in Alaska, most of these vessels were mobilized from the lower 48 states. Some of the support vessel requirements were:

- Skimmed oil/water storage.** Five large (25-50,000 barrels) tank barges were used for storing and transporting oil and water from skimming operations.
- Boat and boom cleaning vessels.** It was necessary to clean response vessels before they left the cleanup areas and to clean other vessels that incidentally became oiled before they could enter harbors. Boat washing stations were established that generally consisted of a work barge, pontoon floats, and associated pumping, washing, and oil containment equipment. Boom washing stations were set up on barges to clean oiled boom.
- Repair vessels.** Two major repair facilities were set up in Prince William Sound. One facility consisted of three barges moored together, including a crane barge. A second facility consisted of two floating dry docks, a crane barge, a slop barge, and an accommodations barge as shown in Figure 8. The floating dry docks were also used for boat cleaning.
- Clinic barge.** A fully staffed medical clinic was established on a barge to provide medical services in the vicinity of the operations.
- Kelp/popweed washer.** During the early days of the spill response there was concern that major quantities of oiled kelp and popweed would be encountered. In response, a hot water washing system was constructed on a barge and a series of collection and disposal vessels were mobilized. Ultimately, little oiled kelp was found.

Aircraft and onshore support

Aircraft operations. At the peak, 85 fixed wing aircraft and helicopters were used in support of the cleanup and animal rescue operations. During these peak months, five thousand to six thousand flight hours

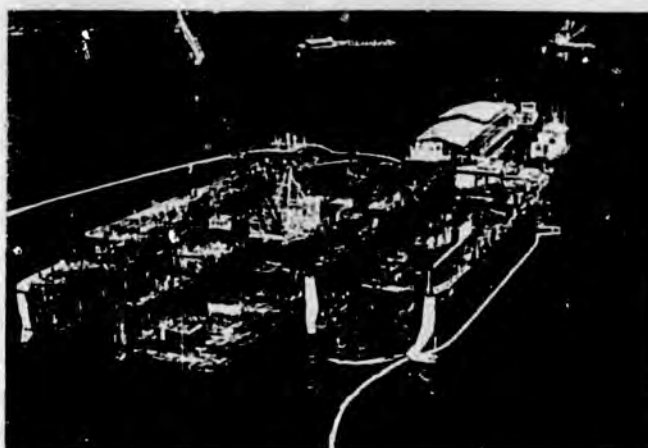


Figure 8. Dry dock repair facility

were required to transport about 20,000 passengers and 800,000 pounds of cargo. Over 20,000 total flight hours were experienced in 1989. Exxon weather criteria (flight minimums) were established to ensure safety and uniformity of air operations. Operations offices were established at the Valdez, Cordova, Homer, Seward, and Kodiak airports. A floatplane base was established on a lake near Valdez. Flight following was employed to monitor aircraft positions and thereby reduce the time required to locate and rescue the crew and passengers in the event an aircraft went down. Fuel caches were provided in remote areas for helicopter refueling.

Telecommunications. Extensive telecommunications facilities were required because of the large operating area, limited existing facilities, and mountainous terrain. Locations of telecommunications facilities changed throughout the operating period in response to the changing spill response needs.

Major fixed repeater stations were established on mountain peaks or other locations to provide broad coverage. These fixed repeaters were supplemented with small solar-powered, mobile repeaters that were moved many times during the spill response to reach specific bays or locations. VHF-UHF translator repeaters (Figure 9) were developed to reduce frequency crowding and meet special frequency needs. Ultimately, the telecommunications network included UHF, VHF, and HF radio systems, microwave stations, satellite stations (INMAR-SAT), and improved mobile telephone service (IMTS) as summarized in Table 3. Exxon was authorized to use all available frequencies, including the entire business radio spectrum.

Onshore berthing, offices, and food. Approximately 4,000 onshore support personnel were involved, with the majority located in Valdez.

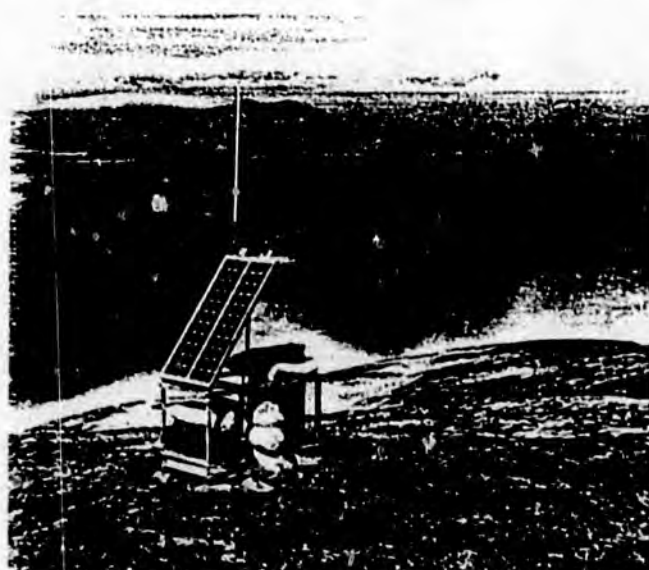


Figure 9. Translator-repeater on Kodiak island

Table 3. Telecommunication equipment used during spill response

Systems	Number used
Wide area UHF radio system	50 fixed repeaters 600 mobile radios 2,040 hand-held radios
VHF—AM and FM radio systems	15 base stations 200 mobile radio 1,150 hand-held radios
Translator repeaters	15 repeaters
HF—single sideband	30 radios
Microwave radio stations	4 fixed stations
Satellite communications	5 earth stations 15 INMARSAT terminals
Improved mobile telephone service (IMTS)	3 systems
Telephone systems	5 PBXs 27 key systems 517 lines and trunks

Housing for these personnel was provided by a number of means including all available hotel/motel space, private homes functioning as "bed and breakfasts," portable camps, and mobile homes. Food catering was provided to accommodate the expanded population in Valdez. Exxon's Valdez Command Center began in a hotel conference room. It later moved into available office space and then into a dedicated building erected by Exxon.

Transportation. Although truck and sea transport were used where feasible, the need for speed led to air shipment of most equipment and materials. At one point, all available commercial cargo flights were on contract to Exxon. Additionally, Exxon used the maximum military airlift capability possible while still allowing for national defense. Because of restrictions at the Valdez airport, most of the equipment delivered by air was flown to Anchorage and transferred to smaller aircraft. Air shipment continued to be the primary means of transport throughout the cleanup, since equipment and materials were needed as soon as they could be manufactured. More than 15,000 tons was shipped by air.

Weather forecasting. Throughout most of the oil spill cleanup operation, weather forecasts were provided by the National Oceanic and Atmospheric Administration (NOAA) and supplemented by local observations. Special forecasting arrangements were made for work on the Barren Islands due to the variability and potential severity of wind and sea conditions in that area. To enhance safety during the period of typically worsening weather leading up to September 15, a specialized contractor was hired to provide more frequent weather monitoring and forecasting within Prince William Sound.

Security. Almost 400 personnel were employed for security in Alaska at the peak of operations. Security functions included controlling access to facilities, providing bear guards on the shorelines, monitoring for alcohol and drugs, and safeguarding personnel and equipment.

Contracting and procurement. Contracting and procurement functions were performed both by Exxon and prime contractor personnel. Vessel contracting was complicated by the speed of mobilization, limited availability of vessels, and the need for some Jones Act waivers for foreign flag vessels. Approximately 1,000 separate contracts were involved and literally thousands of purchase orders were issued, which led to creation of a major data base.

Waste management

The cleanup effort generated quantities of both oily and non-oily liquid and solid wastes. Management of these wastes required extensive facilities for collection, temporary storage, transport, processing, and safe disposal. Final waste disposal methods included landfill, incineration, treatment, or recycling.

Solid waste handling and disposal. Oily solid waste from Prince William Sound, where shoreline cleanup techniques focused on water

washing, consisted mainly of oiled sorbent materials and shoreline debris. In the Gulf of Alaska, the wastes were primarily oily sand and gravel collected as a result of removing mousse patties and tarballs from the shoreline. The initial plan was to incinerate most oily solid wastes offshore on two specially constructed barges. Due to delays in permitting, however, an alternative plan for secure landfill disposal was implemented. Table 4 summarizes the disposal quantities by method. In addition, there was a considerable amount of non-oily solid waste, which included household refuse as well as wood and metal waste, that was sent to municipal landfills in Alaska. The major steps and facilities included:

- **Waste handling.** Oily materials from shoreline cleanup were put in plastic bags and taken to central storage or staging barges equipped with cranes and watertight containers. "Circuit" barges and vessels transported the waste containers to shore. Facilities in Valdez and Seward were constructed to receive, separate/sort, store, transship and/or incinerate oily solid waste. The layout of the Valdez site is shown in Figure 10.

- **Repackaging and landfill operations.** Oily solid waste was transported to repackaging sites in Anchorage and Seward. These facilities reduced the waste volume by shredding, added absorbent material to stabilize free liquids, and packaged it into one and one-half cubic yard bags called "supersacks" for disposal in an out-of-state landfill.

- **Incineration.** To begin disposing of the anticipated large quantity of oily solid waste, Exxon utilized five small onshore incinerators until higher capacity waste handling facilities were available. Two air curtain incinerators were tested, but standard air emission limits on particulates could not be applied to an incinerator without an exhaust stack, and operating permits were not issued.

One of the two incinerator barges (Figure 11) had a silo hearth incinerator with an operating capacity of about 40–70 tons per day. It was chosen for its early availability, positive emissions control system, simple and reliable operation, ability to directly feed large waste materials, and ability to burn high-BTU waste. Although startup was delayed by permitting until nearly the end of the operating season, the unit did operate long enough to conduct air emissions tests. It burned about 500 tons of waste, which was a fraction of its intended use. The other incinerator barge had a rotary kiln incinerator with a projected disposal capacity of 120 tons per day for oil sand and gravel. Permitting also delayed startup of this barge, and further permitting and mechanical problems prevented its use.

Liquid waste handling and disposal. Several hundred thousand barrels of liquid wastes, with the largest amount of this being skimmed oil and water, were generated and disposed of.

- **Skimmed oil and oily water.** Free water from skimming activities and other oily waters were transported to Alyeska Pipeline Service Company's Valdez terminal for processing through its ballast water treating system. Emulsified oil and water from skimming operations were transported to Seattle or to Exxon's Baytown refinery for processing, oil recovery, and waste water treating.

- **Sanitary waste.** Offshore discharge of untreated sanitary wastes from berthing vessels was not allowed, and this waste was transported to the Valdez municipal treatment system. Later, a barge was modified to serve as an offshore treatment facility.

Table 4. Summary of oily solid waste disposal

Processing facility	Tons processed
Incineration	
Onshore incinerators	2,100
Silo incinerator barge	500
Total incineration	2,600
Lower 48 landfill	
Anchorage repackaging facility	15,900
Seward repackaging facility	6,500
Subtotal	22,400
Absorbent added in processing	8,000
Total landfill	30,400
Total oily solid waste disposal	33,000

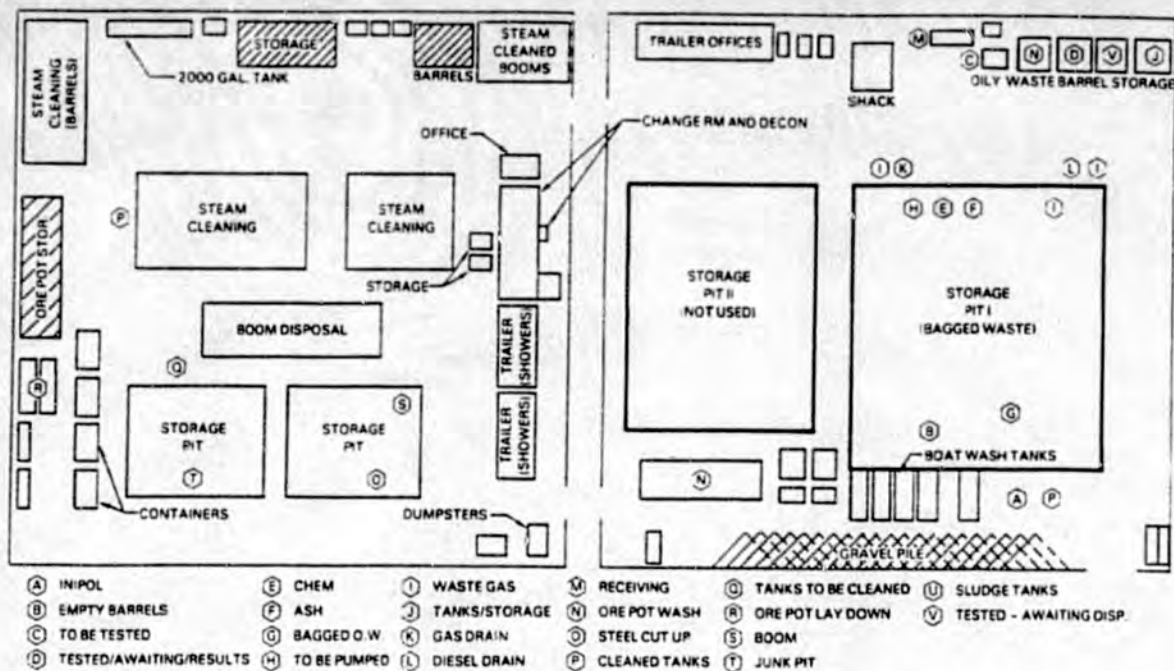


Figure 10. Layout of Valdez waste handling site

• **Cleaning waters.** Oily washwater generated from cleaning boats, protective gear, or booms, was pretreated to reduce the oil and grease to levels acceptable for treatment in the Valdez municipal treatment facility.

Hazardous wastes. The spill cleanup wastes were not classified as hazardous under state and federal laws, but some associated wastes were and required special handling and disposal in out-of-state facilities.

Demobilization

During early June, Exxon began to plan the demobilization of the cleanup operations and the transition to the 1989-1990 Alaska winter program. A review of historical weather patterns showed that by the middle of September offshore operations would have to cease because deteriorating weather conditions would seriously impact the safety of

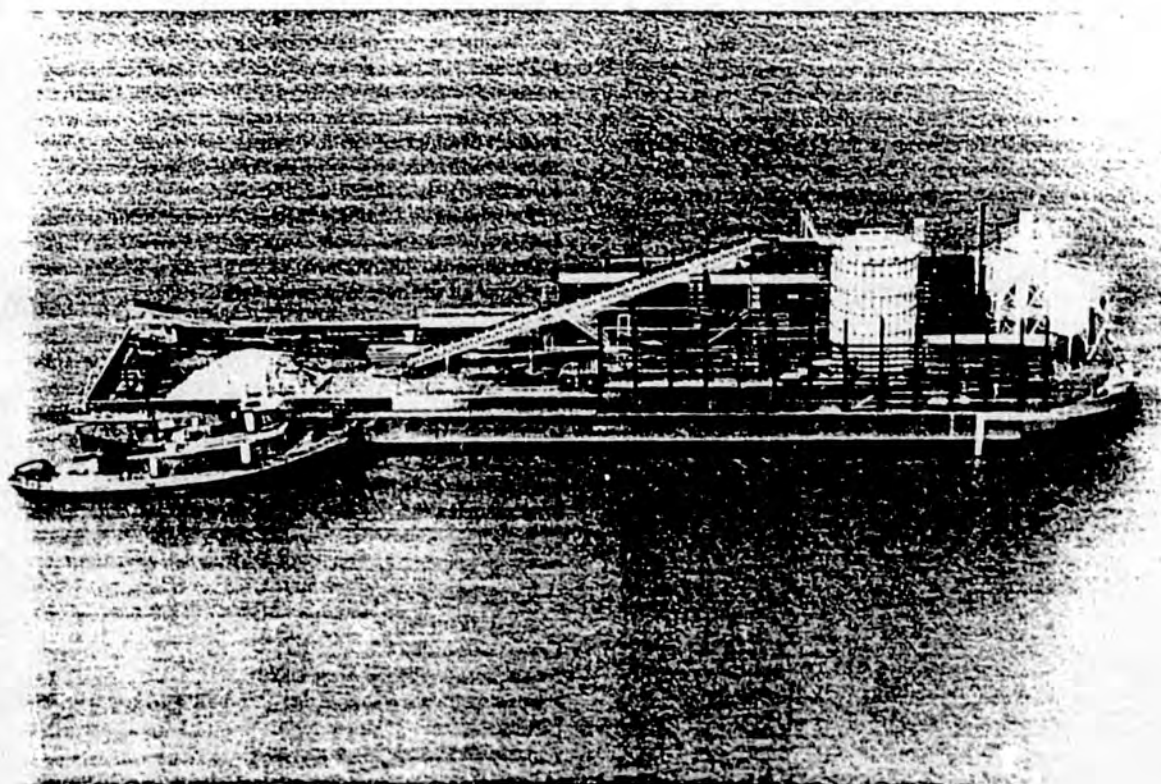


Figure 11. Barge mounted silo incinerator

the cleanup. A demobilization schedule was prepared that permitted work to continue as long as possible and still allow vessels to transit safely to their home ports before the forecasted onset of weather conditions that would exceed each vessel's operating limits. Vessel demobilization was complete in late October.

Vessel data base. The large number of vessels involved in the cleanup operation and the short demobilization period made it imperative for the supervisors of this operation to have an accurate knowledge of the vessels, owners, charter terms, and off-hire redelivery ports with which they would be dealing. A demobilization vessel data base was put together from several operating data bases to meet this need. This data base was used to schedule sailing plans for vessels and to monitor status of the program.

Vessel preparation and cleaning. All vessels were cleaned of oil as part of demobilization; additional vessel cleaning stations were established to meet this need.

Within Valdez harbor, demobilization facilities for equipment removal included three shore sites, three crane barges, and two staging areas with moorings. A separate complex in Louis Bay, including a derrick barge, was used for dismantling sectional barge assemblies.

Transit to home port. For the transit to home port, the larger barges were used to transport equipment and smaller vessels. A tow survey was conducted prior to departure to ensure that the vessels and tow hardware were safe and seaworthy. When the vessel reached its home port and was ready to go off-hire, a surveyor representing Exxon and a representative of the owner inspected the vessel.

AN OVERVIEW OF THE EXXON VALDEZ OIL SPILL

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ABSTRACT: While the Exxon Valdez oil spill had a significant and far-reaching impact, important progress has been made since the massive cleanup operation was launched in the spring of 1989. In 1989, Exxon treated almost 1,100 miles of shoreline identified to be impacted. This effort involved more than 11,000 people and 1,400 marine vessels. Environmental recovery is well under way in areas impacted by the spill, thanks to nature's own cleansing power and man's efforts. The 1990 cleanup primarily used nonintrusive techniques and addressed 10 to 15 percent of the shoreline treated in 1989. Much has been learned about how to prevent and respond to such an incident in the future.

Early in the morning on Friday, March 24, 1989, the *Exxon Valdez*, a 987-foot, state-of-the-art tanker carrying 1.25 million barrels of North Slope crude oil, ran hard aground on Blight Reef in Alaska's Prince William Sound. The grounding left 8 of the vessel's 11 cargo tanks and 3 of its 5 ballast tanks holed extensively, causing some 258,000 barrels of crude to spill into the water, most of it within the first few hours.

The spill occurred in a remote location in open water, in an undeveloped area of rugged terrain where boats and aircraft provided the only access to the impacted areas (Figure 1). The site was far from major population areas—about equidistant from New York and Tokyo and more than 3,000 miles from Exxon USA's principal operations along the Gulf coast of the United States. Exxon is not an operator in Alaska, and at the time of the accident, only a couple of dozen Exxon employees were in the entire state.

Immediately following the accident, the tanker captain notified the U.S. Coast Guard. Consistent with the oil spill contingency plan developed by the Alyeska Pipeline Service Company (operator of the marine terminal in Valdez) and approved by both federal and state authorities in 1977, and again as recently as January 1987, the initial spill response was carried out by Alyeska and the U.S. Coast Guard. It is important to note that the contingency plan focused on spill sizes of 1,000 or 2,000 barrels, in the belief that these were "most likely" to occur. It specifically recognized that a spill in the 200,000-barrel range could not be fully contained, and that a significant amount of oil would reach shore.

Exxon's response

From its offices in Exxon USA's headquarters building in Houston, Exxon Shipping Company began to mobilize the Exxon response team. A command center was established in Houston before dawn, and phone calls were placed around the world to locate and assemble needed materials and equipment. Arrangements were made for the first of many flights to Alaska to airlift equipment from oil spill cooperatives and other organizations. The Exxon response team left Houston by air before 8:30 a.m., arriving in Valdez by 5:20 p.m. on the

day of the spill. Dozens more trained people and tons of supplies began arriving that same day.

When Exxon's team arrived, they found the *Exxon Valdez* impaled precariously on a reef, in imminent danger of capsizing. The threat to the crew and the remaining cargo—another million barrels of oil, four times the amount spilled—was an immediate concern. One of the most pressing tasks was clear: to transfer—or lighter—the remaining crude to other tankers and keep the ship afloat.

Lightering operations began the morning after the spill. Transferring the million barrels of crude oil that remained in the *Exxon Valdez* to other tankers was an extremely delicate operation. Three tankers were diverted to the site and each was carefully maneuvered alongside the grounded vessel to offload the oil. Every barrel of oil removed was replaced with sea water to avoid potentially disastrous shifts in weight. Within 10 days, a small group of Exxon Shipping Company employees, displaying superb seamanship and on-the-spot technical innovation, successfully removed all the remaining cargo—and with it the threat of a much greater spill.

Simultaneously, the effort began to contain and clean up the oil that had already spilled.

To reduce substantially the volume of oil that might reach land, the contingency plan stressed the importance of the early use of dispersants and open burning. Unfortunately, there were inordinate delays in obtaining approval from the authorities for these methods.

A severe storm at the end of the third day following the spill spread the oil slick over a distance of 40 miles and onto island shorelines. At that point, containment was no longer possible, and cleanup became a key priority.

Wildlife. Another concern was the rescue and treatment of animals affected by the spill, and Exxon immediately committed extensive resources to this effort. From March through September of 1989, Exxon organized the largest and most comprehensive bird and sea otter rescue and rehabilitation program ever attempted. Facilities for holding, cleaning, and caring for oiled birds and otters were built in Valdez, Seward, Homer, Kodiak, and Anchorage. The rescue and rehabilitation efforts were overseen by established experts in the field, who arrived in Alaska within days of the spill.

More than 140 boats were used to retrieve oiled birds and otters from remote locations throughout Prince William Sound and the Gulf of Alaska. More than 700 specialists and volunteers were involved in the rescue and rehabilitation effort. Expenditures for the bird and sea otter programs exceeded \$45 million.

Claims. Exxon also moved quickly to establish claims offices to work with hatcheries, canneries, fishermen's groups, and many individuals to assure their financial viability through a system of advance payments.

The first claims office opened in Valdez on March 31, 1989, a week after the spill, and funds were available locally that same day. By the end of the summer of 1990, Exxon had paid over \$230 million to more than 12,000 fishermen and other claimants.

Mobilization. At the same time that Exxon was removing oil from the vessel, caring for wildlife, and launching a claims program, inten-



Figure 1. Map of Exxon Valdez oil spill site

sive efforts were under way to assemble the personnel, equipment, and supplies needed to implement the cleanup.

Bringing about this mobilization required a tailor-made organization that addressed every aspect of the cleanup effort, including planning and coordination, logistics, operations, technical and accounting, public affairs, and telecommunications.

Assembling the necessary people was the key to this mobilization, and that effort accelerated rapidly over time. Twenty-four hours after the spill, Exxon had 35 employees on the scene, and had hired 200 others. After one week, 800 people were dedicated to the effort; after one month, 3,000—and that number nearly quadrupled at the height of activity in the summer of 1989 (see Figure 2).

People were added as quickly as equipment arrived to support their activities. Most of the needed equipment had to be transported from the Lower 48 states, Canada, and several European countries.

Techniques. While this huge mobilization progressed, Exxon began to focus on what was needed to treat the affected shorelines. It became clear that two different kinds of operations had to be mounted because two different sets of cleanup problems existed.

In Prince William Sound, the shoreline is largely a collection of rocks of varying sizes, and this effectively determined what cleanup methods would be developed and tried. The principal cleaning method was to wash the oil from the rocks, using warm or cold water, or both (see Figure 3). The oil loosened by this washing was flushed into the sound, where it was contained by booms, picked up by skimmers, and held for subsequent treatment in onshore separation facilities.

In time, Exxon had to find innovative methods to bring more water for use on the shorelines. Accordingly, what came to be the workhorse piece of equipment for this phase of the cleanup—the maxi-barge—was developed. These custom-built barges had a crew of about 50, some 10,000 feet of boom, a couple of oil skimmers, fuel and storage tanks, a 225 kw generator, and several water heaters (Figure 4).

Many of the maxi-barges had a piece of equipment that made it possible to treat shorelines that could not be reached by foot. This device was called an "omni-boom," a hydraulically articulated delivery

system normally used for pumping concrete on construction projects (Figure 5).

At the peak of operations, systems capabilities were substantial: the ability to heat enough water to serve a city of half a million people. Overall, some 200 million gallons were delivered daily—enough to meet the needs of a city of one million persons.

Operations varied somewhat in the Gulf of Alaska, where the terrain was different and the impacts of the spill were less severe. There, the shorelines are less rocky and more sandy than those in the sound; more like what most people envision when they think of beaches.

Largely, the cleanup job entailed collecting, by rake and shovel, oily sand and tar balls, and disposing of the debris in plastic bags. In about six months, workers collected some 25,000 tons of solid wastes. Most of this waste material was sent to a landfill in the Lower 48 states.

Bioremediation. One of the most promising cleanup methods developed to deal with the spill was bioremediation. It has long been known that certain microbes have a taste for the complex hydrocarbons that make up crude oil. They ingest these hydrocarbons and break them down into harmless water and carbon dioxide.

The Environmental Protection Agency, working jointly with Exxon, undertook a test program that was encouraging. It led to using bioremediation on selected areas of shorelines. In all, in 1989 about 70 miles were treated with nutrients that supported these microorganisms.

Results. In the spring and summer of 1989, Exxon treated a total of nearly 1,100 miles of shoreline identified to be impacted—about 360 miles in Prince William Sound and more than 730 miles in the Gulf of Alaska—leaving them in an environmentally stable condition, safe for wildlife (see Figure 6 for cleanup timetable). While this was a major undertaking, it is important to bear in mind that the oil spill affected less than 15 percent of the total shoreline in these two areas.

At the peak of activity, the cleanup effort involved more than 11,000 workers—of whom about 3,500 were working directly on the beach—as well as some 84 aircraft and more than 1,400 vessels of all types.

In such a labor-intensive operation, safety was of the highest prior-

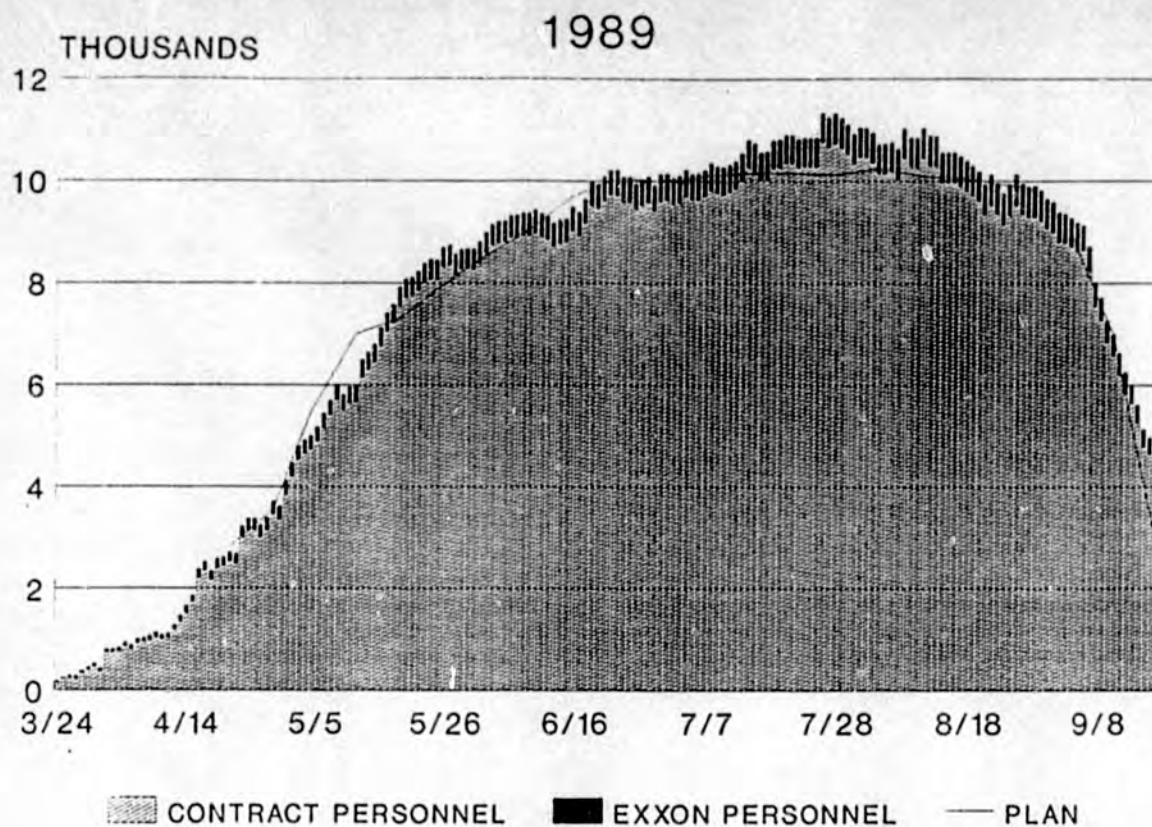


Figure 2. Personnel employed in oil spill response effort

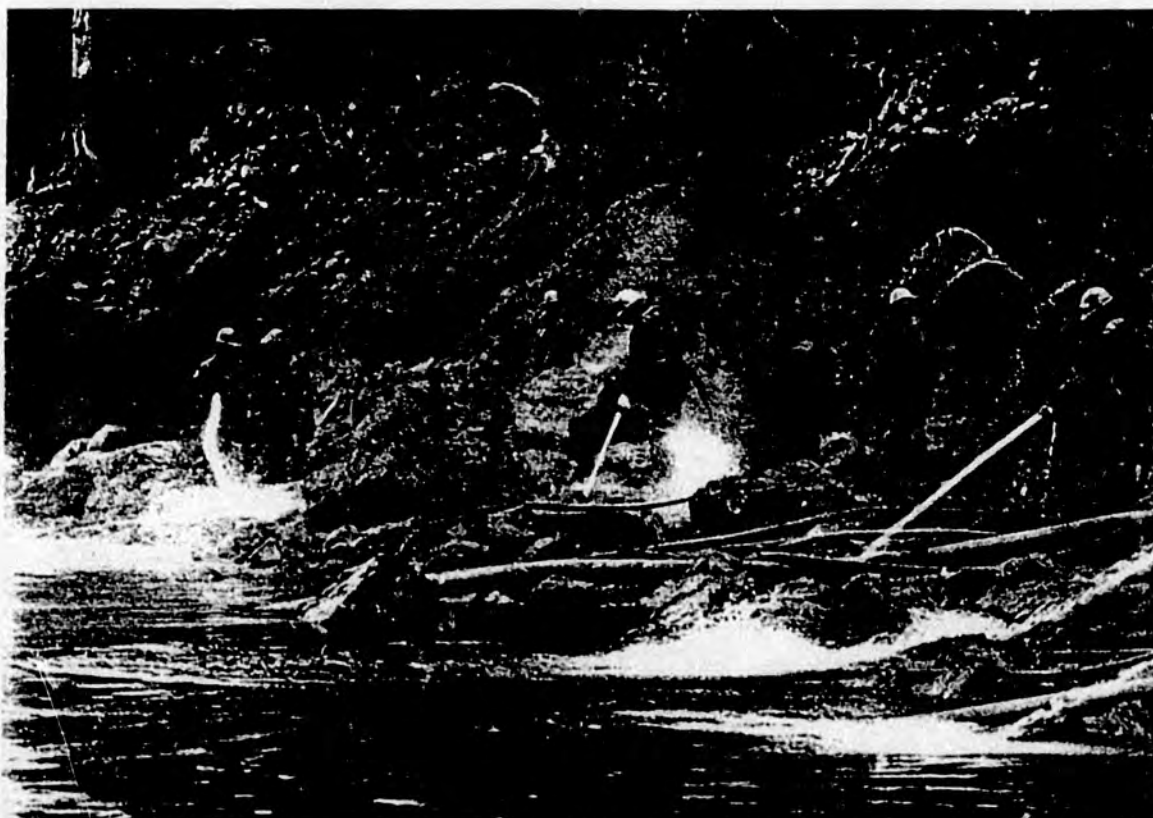


Figure 3. Washing oil from rocks in Prince William Sound



Figure 4. Maxi-barge working at shoreline

ity, and Exxon was pleased with its performance. There were 24.9 total recordable accidents per million manhours, which compares to 38 for heavy construction in general and 107 for non-residential construction.

Winter 1989-90

By mid-September, weather conditions required that shoreline activities be phased down because of the serious risk of life posed by the onset of the arctic winter. In Prince William Sound, winter gales can create waves 10 to 15 feet high, while 30-foot waves are common in the Gulf of Alaska. Wind speeds in the area are shown in Figure 7. Temperatures plunge well below freezing, and daylight diminishes to five hours per day by the time of the winter solstice.

Exxon maintained a large presence in Alaska over the winter and carried on a multifaceted program. More than 700 Exxon and contract employees remained at work, most based in Anchorage, where equipment also was maintained. Ships, aircraft, and other materials were strategically deployed in Anchorage, Valdez, and other communities. A number of people residing in Alaskan villages, who worked in the summer cleanup effort, were retained on "call up" status as a contingency strike force. Sixteen villages were under contract to Exxon to conduct winter shoreline monitoring of designated beach areas.

In addition, Exxon's comprehensive winter science program encompassed more than two dozen environmental field studies, involving some 300 scientists and technicians from all over the United States.

As anticipated, both in Prince William Sound and the Gulf of Alaska, fierce winter storms made major improvements on high- and moderate-energy shorelines. In the areas where it was applied, bioremediation enhanced those natural processes. As a result, the condition of the shorelines continued to improve.

Environmental recovery

By the spring of 1990, it was clear not only that shoreline conditions had markedly improved, but also that environmental recovery was well under way (see Figure 8).

In April, three distinguished scientists from the United Kingdom visited Alaska to conduct field observations on the environmental impacts of the spill. One of their principal observations was: "Only a portion of the shoreline had been oiled, and, as with most other oil spills, the bulk of the damage had disappeared during the first year. The area has retained its natural beauty; there are abundant signs of plant and animal life, and recovery is well under way on even the most severely impacted beaches."¹

Equally encouraging results were seen in studies of water quality. In the spring of 1990, findings were published based on water quality studies conducted by four prestigious research organizations: Arthur D. Little Marine Sciences, Battelle Ocean Sciences, Kinetic Laboratories, Inc., and America North, Inc.

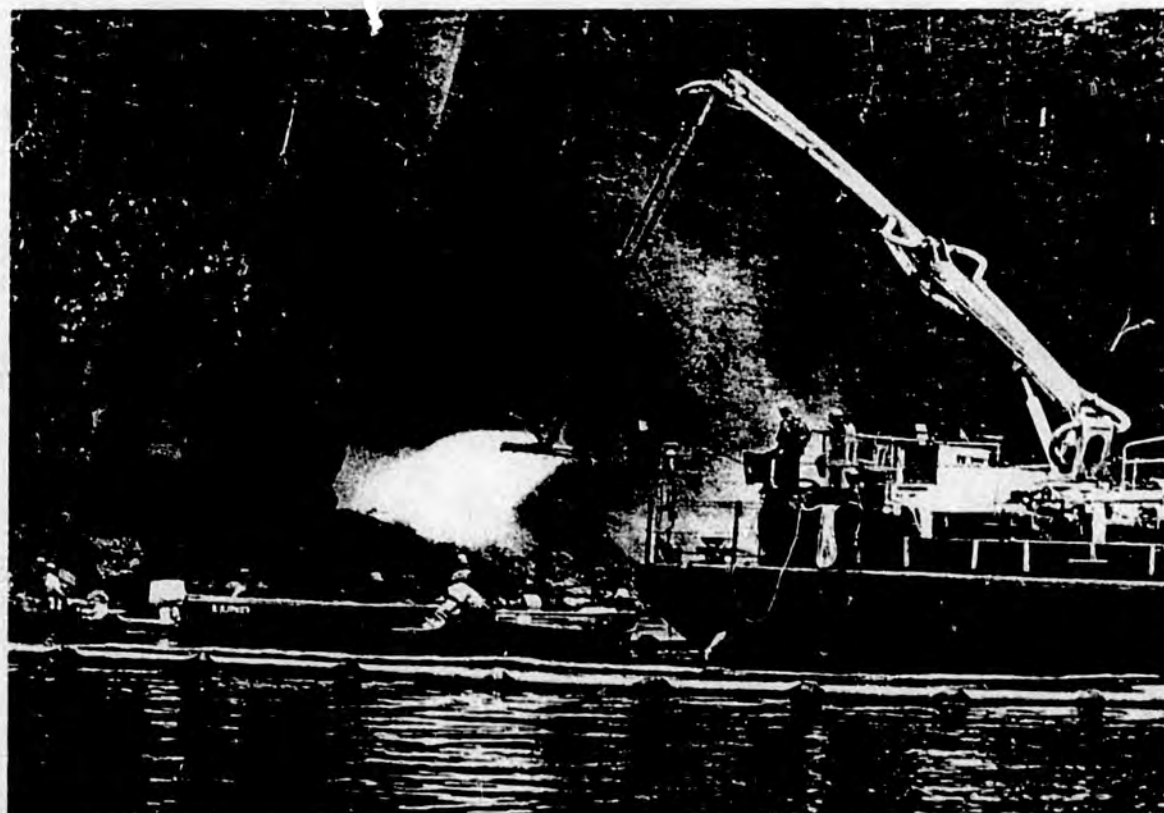


Figure 5. Omni-boom spraying water on shoreline

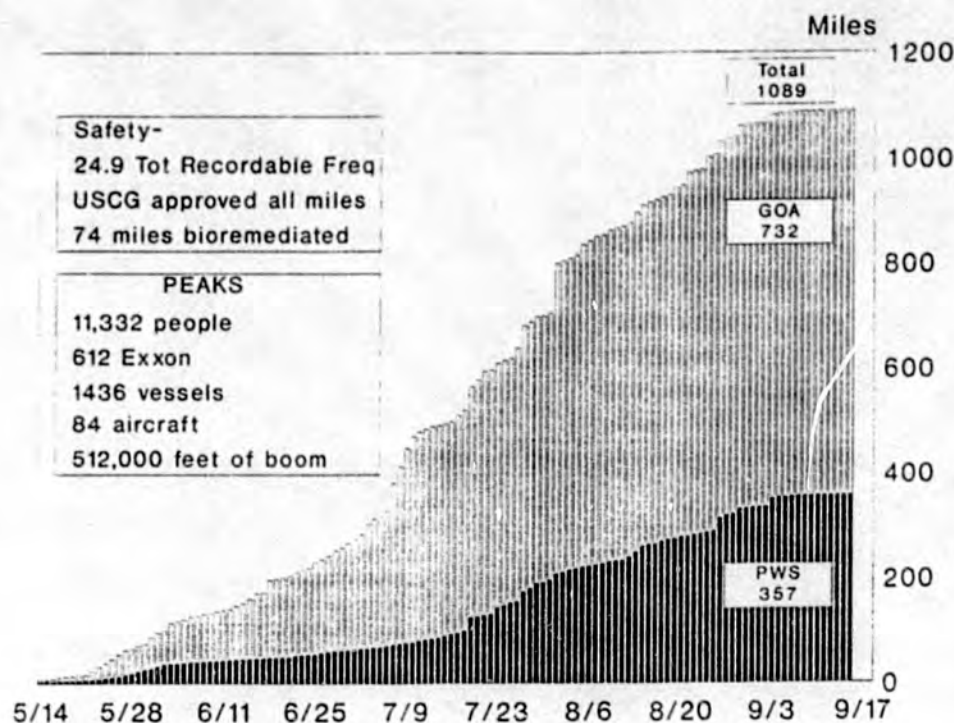


Figure 6. Graph of 1989 shoreline cleanup progress

Dr. Jerry M. Neff, a Battelle scientist, reported that average aromatic hydrocarbon concentrations in the waters of Prince William Sound had remained well below State of Alaska standards. Over 2,300 water samples were taken from the sound and all had shown consistently low hydrocarbon levels since April of 1989. In most cases, the levels were 10 to 1,000 times below the concentrations found to cause harm to marine animals. In addition, he concluded, "It is extremely unlikely that hydrocarbon concentrations resulting from the spilled oil have had or will in the future have any adverse effects on plants and animals living below the surface in the water column of Prince William Sound, including commercial fishery species."²

This judgment was confirmed by the fact that commercial fishermen realized highly successful catches in 1990, including a record-setting pink salmon harvest in Prince William Sound. Moreover, field observations confirmed a large number and diversity of birds, otters, and other mammals thriving in the spill-impacted area. Given the 10 million seabirds and 12,000 otters in the affected area and their natural resiliency, all species were expected to recover rapidly.

Spring and summer 1990

The major objective of studies conducted over the winter was to assess the need for additional work and to make plans to conduct whatever activities were needed in the spring and summer of 1990. While winter storms and tidal actions further cleaned the shorelines, particularly those exposed to higher and moderate wave energy, some areas required additional cleaning and Exxon performed that task over the summer.

The 1990 cleanup focused on techniques that were least intrusive to the recovering environment while achieving the desired results. Over-

all, the objective was to complete the appropriate cleanup work in a way that provided a further net benefit to the environment, minimized the negative impacts on wildlife, did not interfere with fishing, and enhanced the natural recovery that had already begun.

Consistent with these goals, principal cleanup methods used in 1990 included manual oil removal, tar mat removal, spot washing, tilling and raking, and bioremediation. Some 1,000 people and 70 vessels were involved in the 1990 cleanup operation, which re-treated 10 to 15 percent of the total shoreline mileage treated in 1989.

The U.S. Coast Guard monitored day-to-day shoreline operations, with extensive technical support from the National Oceanic and Atmospheric Administration (NOAA). The professionalism and technical and operating expertise provided by these key government agencies were an important factor in the success of the 1990 effort.

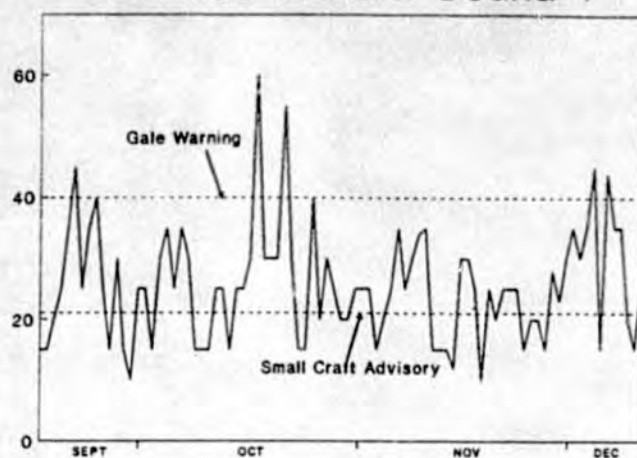
A joint shoreline assessment program was conducted in August 1990 to identify sites for possible re-treatment in 1990 and to recommend priority sites for reassessment in 1991.

It's expected that by the spring of 1991, few areas will remain with any significant oil and there will be no visible oil or stains on areas treated in 1990. Isolated pockets of subsurface oil will likely still remain, particularly in wave-sheltered areas. However, NOAA concluded in July 1990 that "deeply buried subsurface oil . . . poses little risk of causing further significant environmental injury."

Lessons learned

As difficult as the spill and cleanup experience has been, it has yielded some important lessons about the management of such a crisis. That better advance preparation is needed for what to do when such an emergency occurs is obvious. The American petroleum industry has

Prince William Sound



Gulf of Alaska

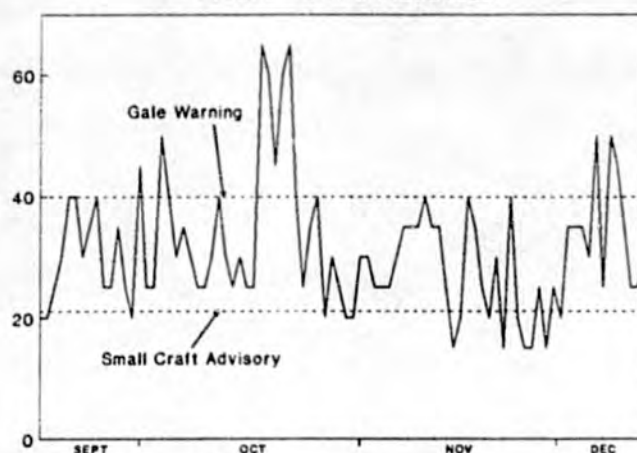


Figure 7. Graphs of 1989 winter wind speeds in knots

already taken this to heart in a plan for a series of response bases located along the coasts of the United States—the Petroleum Industry Response Organization, or PIRO. The proposed equipping and manning of these bases will be at a level far exceeding anything seen before.

Similar measures are adopted at the terminal operator Valdez, which as stockpiled additional boom, barges, and other spill-related equipment.

In addition, interim steps have been taken regarding vessel transit in and out of the port of Valdez. These include escorts and extending the distance from port during which a pilot must be onboard.

In the event of a spill, however, putting added resources to effective use is not an automatic process. Timely, effective action—the kind needed in an emergency—cannot be taken by committees. When several groups with different priorities and differing views about what should be done jointly face an urgent need for action, too often the outcome is conflict and no action at all—or, at best, a lowest common denominator approach. The larger interest tends to get lost in the give and take. Someone who can weigh the issues, cut through the disagreements, and force timely action must clearly be in charge. Most logically, that someone should be the U.S. Coast Guard.

Another area for close examination is the pre-approval of cleanup technology. Clearly, dispersants are the key to responding to a large spill, and their use must be cleared *in advance*—as if often done in Europe—if timely and effective action is to be taken. The same is true concerning the use of chemical cleaners, and even the more basic methods such as warm-water washing. Unfortunately, in the case of the Valdez spill, chemical cleaners were approved only in tests, and heated wash water temperatures were approved only in increments.

While speed and decisiveness are critical to effective spill response, the procedures in place in the United States are hardly conducive to either. Federal, state, and local authorities—as well as industry—have to develop a more effective response procedure in the event of an emergency. When it comes to a crisis, the federal government, which is best positioned to have the necessary technical expertise and to balance the diverse interests of the myriad of local, state, and national agencies involved, must have clear authority and the confidence to act decisively.



Figure 8. Seagulls off Green Island, April 1990

Changes within Exxon

Exxon has taken a number of specific steps to reduce the risk of oil spills and to strengthen cleanup capabilities.

Procedures have been revised concerning employee substance abuse to require random testing of employees in designated safety-sensitive positions, such as certain refinery and chemical plant operators, tanker officers, aircraft pilots, and tank truck drivers. No one who has, or has had, a dependency will be permitted to occupy such a position.

Exxon operating units in the United States and foreign affiliates have reviewed their oil spill prevention plans and response capabilities and have increased the amount of response equipment at their marine terminals. Collision warning systems for tankers are being upgraded with more sophisticated, integrated bridge navigation systems. Additional remotely-operated pipeline block valves have been installed where lines cross rivers or sensitive areas. Oil storage has been eliminated in exposed wing tanks of the Exxon offshore processing vessel in

California. And the frequency of vessel inspections of Exxon's fleet has been increased to as much as twice per year.

In addition, a new senior executive level position of Corporate Vice President, Environment and Safety, has been created to further assure that Exxon's environmental responsibilities are fulfilled.

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