NOAA Technical Memorandum NOS ORCA 73

Evaluation of the Condition of Prince William Sound Shorelines Following the Exxon Valdez Oil Spill and Subsequent Shoreline Treatment:

Volume I Summary of Results—Geomorphological Shoreline Monitoring Survey of the Exxon Valdez Spill Site, Prince William Sound, Alaska September 1989-August 1992

October 1993
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noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

National Ocean Service

Office of Ocean Resources Conservation and Assessment
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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Volume I Summary of Results—Geomorphological Shoreline Monitoring Survey of the Exxon Valdez Spill Site, Prince William Sound, Alaska September 1989-August 1992

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ACKNOWLEDGMENTS

This study is part of the continuing monitoring survey sponsored by the Hazardous Materials Response and Assessment Division of NOAA, David M. Kennedy, Division Chief, and Robert Pavia, Project Technical Representative. The chemical analyses were carried out at the Environmental Studies Institute, Louisiana State University (LSU), under the supervision of Charles B. Henry. Todd M. Montello of Research Planning, Inc. (RPI) and Paulene O. Roberts of LSU assisted the authors with the field work during the August 1992 survey. Graphics and other technical support were provided by Joe Holmes, Jeff Dahlin, Dot Zaino, Becky Cox, and Tom Simpson of the RPI staff.

EXECUTIVE SUMMARY

Since September 1989, the Hazardous Materials Response and Assessment Division of the National Oceanic and Atmospheric (NOAA) has sponsored a geomorphological and chemical monitoring program at 18 stations in Prince William Sound, Alaska. The original purpose of this program was to provide the technical basis for development of shoreline treatment requirements in 1990 and beyond. The program has been continued to provide a physical framework for a concurrent biological monitoring program, to evaluate the effects and effectiveness of specific shoreline cleanup methods (such as berm relocation), and to study the special problem of oiled gravel beaches. The August 1992 field season also included a joint project with chemists from LSU to characterize the chemical weathering patterns of residual oil 3.5 years post-spill. The objective of this special study was to collect samples of the various types of residual oil, in close cooperation with the geomorphological studies, so that the interpretations would include an understanding of the physical setting and processes which have contributed to the weathering history. This report presents the results of the August 1992 survey and a summary of the persistence of oil in representative shoreline environments. Special emphasis has been placed on presentation and summary of the subsurface oiling patterns and changes over time.

Of all of the shoreline environments in Prince William Sound, the *cobble/boulder platforms with berms* have proven to have the greatest potential for long-term persistence of significant quantities of oil. These shorelines have unique characteristics that make them different from what are considered to be "typical" gravel beaches. Even though they occur along the shorelines that are most exposed to storm-wave action, the oil had penetrated deeply into the substrate, to depths below that normally reworked by annual storms. All of the heavily oiled shorelines of this type were treated by various techniques, including hot-water washing, nutrient addition, berm relocation, tilling, and manual removal. By the end of summer 1992, nearly all of these beaches were free of surface oil. The only exceptions were at two of the sites where extensive berm relocation had been conducted in either 1990 or 1991. There were very different patterns in the persistence and distribution of subsurface oil, based on development of armor on the upper and lower platform, mobility of the gravel on the platform, slope, and thickness of the sediments overlying the bedrock platform, as discussed below.

On beaches with steep, shallow bedrock platforms and mobile sediments, very little subsurface oil remained anywhere along the profile by August 1992. An example of this gravel-beach type is station N-17 on Perry Island, which contained only a trace of oil stain on the cobbles in the high-tide berm area where the spring berms had been relocated. Station N-4 on Smith Island is another example of this shoreline type. These beaches tended to have somewhat finer-grained sediments, which were also more mobile. Many beaches of this type had undergone successful berm-relocation projects in 1990 to speed the removal of oil stranded in the higher spring-tide and storm berms.

In contrast, on beaches in the cobble/boulder platforms with berms class with flatter, deeper bedrock platforms and well-established armor on the upper and lower platform, significant quantities of subsurface oil remained 3.5 years post-spill. These beaches were different in that the grain size of the surface sediments on the platforms was coarser, which effectively immobilized the substrate (and oil) underlying the armor, the oil could penetrate more deeply into the sediments on top of the bedrock platform, and hydraulic flushing was impeded. The normal erosion and deposition of berms at the high-tide line reworked the sediments to depths of 50+ centimeters (cm) over the first winter, but there was little change in the interval and degree of subsurface oil lower on the beach until after the second winter. By 1991, the top 20 cm or so on these beaches appeared clean. However, there was little change in the degree or extent of oiling at greater depths. By 1992, the interval of oiling in these armored beaches has shown little change, but the degree of oil contamination has visually decreased, from what had been described as heavy in previous surveys to moderate in 1992. Chemical samples have been taken to compare both oil concentrations and weathering. Stations N-1, N-3, N-7, and N-15 are representative of this more stable cobble/boulder platform with berms shoreline type.

Of special interest during this survey period was monitoring the recovery of beaches that underwent extensive sediment excavation, tilling, and relocation, in particular Point Helen (N-1) and northeast Latouche (N-15). The degree of sediment excavation was much greater than that normally conducted as berm relocation, which had been implemented successfully at over 30 sites in 1990. Such extensive treatment was deemed necessary because of the long-term persistence of heavy oil contamination. Treatment included complete relocation of the entire storm berm (such as along Point Helen) and mechanical tilling and excavation of sediments under the upper platform (such as on Latouche Island). These more intrusively excavated beaches had not recovered to pre-disturbance conditions in terms of the beach profile and the sediment distribution patterns as of August 1992. Oil still remained in significant quantities at depth in the mid-intertidal zone at N-15 and N-1.

Two stations were classified as *bayhead beaches with mobile sediments*. On these beaches the gravel is smaller in grain size and the beach sediments are reworked by small streams which drain into the heads of the bays. Surface oil was quickly removed from these beaches, that is, within the first storm season. However, there were large differences in the persistence of subsurface oil, most probably related to sediment grain size. At N-14 in Northwest Bay, the sediments were dominated by granules and pebbles; intensive washing of these sites in 1989 transported a significant amount of these finer-grained sediment into the lower intertidal zone. Subsurface oil concentrations have always been very low. The sediments are slowly returning up the beach profile, as evidenced by swash bars on the lower intertidal zone. In fact, this site had the only occurrence of *buried* oil in these studies in Prince William Sound; the swash bars had buried an asphalt pavement which was being partially exposed in a channel of a small stream cutting across the bar in August 1992.

The station in Sleepy Bay (N-18) is also a bayhead beach, but the sediments are coarser grained and thus less mobile, particularly with depth. Some of the deepest penetration and highest levels of oil contamination in Prince William Sound were recorded for samples from Sleepy Bay. This heavy subsurface oil persisted through the summer of 1991, until a major sediment excavation was conducted. As of 1992, no subsurface oil was observed; the extensive excavation of the mid-tidal zone was effective. Although the topographic profile had returned to normal, the sediment distribution had not returned to its pre-treatment configuration. The coarse rubble and boulder debris remained piled on the mid-tidal zone, and it is predicted that it will be years before the original sediment distribution patterns are re-established. Thus, observations at stations N-1, N-15, and N-18 indicate that berm relocation and sediment excavation should be considered only on a case-by-case, site-specific basis.

Two pebble beaches with tidal flats were included in the monitoring program: one which was treated with hot-water flushing of the upper beachface (N-9 on Block Island); and one that was not (N-11 on Crafton Island). The Block Island tidal flat remains oiled as of August

1992, with patches of heavily oiled sediment just below the surface, whereas the Crafton Island flat showed only very light or no contamination. It may be that, where the lower intertidal zone is relatively flat and contains fine-grained sediments, there is a greater risk of long-term contamination of the tidal flat sediments from washing the adjacent shoreline.

Stations on sheltered rocky shorelines have been divided into two types, rocky shores and rocky rubble slopes, based on the thickness and degree of permeability of the surface sediments. On all *sheltered rocky shores*, treatment and weathering had resulted in steady removal of surface oil, with only 5 to 10 percent coverage of stain after 3.5 years, even at the set-aside sites. Those that were composed of impermeable bedrock, with only some surficial sediments which have formed from normal bedrock weathering, had penetration of oil limited to the top 15 cm, with 5 cm being more common. In contrast, *rocky, rubble slopes*, formed by the passive accumulation of sediments on the bedrock surface, have higher permeability and greater oil penetration and persistence. Natural removal of oil, even from the surface, on these shoreline types was extremely slow.

After 3.5 years of monitoring these stations in Prince William Sound, the following conclusions have been drawn:

- Gravel beaches have proven to be a very difficult shoreline class with regards to predicting natural removal rates and the effects/effectiveness of shoreline treatment methods. In particular, those gravel beaches that are exposed to only intermittent storm waves pose the greatest problems.

These semi-sheltered gravel beaches are a very complex group of shorelines, with a large amount of intra-site variability. Yet, when they are heavily oiled, the result is deep penetration, oftentimes to depths below those of annual reworking. All gravel beaches in Prince William Sound showed persistence of some subsurface oil over the first storm season. This deeply penetrated oil weathered more slowly than surface deposits, creating the potential for chronic sheening for years, even after extensive treatment. Chronic sheening results from oil remaining in the mid-intertidal zone, not from oil that remains in the upper-intertidal or supratidal zones. Berm relocation, which was usually restricted to the spring-tide and storm berms, did appear to speed the removal of oil from these zones by at least one year. It has not been possible to determine whether the relocation of sediments to the upper-intertidal zone slowed the removal of the underlying subsurface oil. The presence of a stable armor on the mid- and lower-intertidal zones was a major factor in slowing natural removal of subsurface oil from these beaches.

- Bayhead beaches composed of small gravel (pebbles and granules) recovered quickly from physically intrusive treatment methods, such as sediment relocation and excavation.

The finer-grained gravel was highly mobile and the sediments were usually returned to their original position within one storm season. The sediments were relatively uniform with depth, so deep excavation was possible without causing significant changes in sediment distribution patterns. However, no direct measurements were made as to loss of the finer-grained fraction to the lower intertidal or subtidal, which would be of concern if these finer-grained sediments were contaminated.

- On sheltered rocky shores that were heavily oiled and were not treated, natural weathering processes reduced the surface oil coverage to less than five percent after 3.5 years. However, these untreated rocky shores appeared to retain residual oil in rock crevices, under rocks, and as asphalt pavements where sediment accumulations occurred.

This conclusion is based more on observations made during interagency shoreline surveys than the NOAA monitoring stations, because of the lack of suitable paired stations that were treated and set aside. The two NOAA stations at the set-aside rocky shores (N-5 and N-6) appeared to have higher amounts of thicker residual oil deposits on the upper half of the intertidal zone than similar, treated shorelines. The more difficult issue is determining the ecological impacts of this residual oil compared to the impacts resulting from treatment activities. Hopefully the chemical analyses of the residual oil from treated versus set-aside sites will generate definitive comparisons in weathering rates.

- Sheltered rocky, rubble slopes have been identified as a special class of rocky shores that have the potential for deeper penetration and persistence of oil. These bedrock shores have a somewhat permeable surface layer of sediments in which oil can persist for long periods. Such shoreline types should receive high priority for both protection and cleanup.

CHAPTER 1
INTRODUCTION

Since September 1989, the Hazardous Materials Response and Assessment Division of NOAA has sponsored surveys of the geomorphological changes and oil distribution at 18 stations throughout Prince William Sound, Alaska. This work originally was designed to provide the scientific basis for decision-making by the U.S. Coast Guard, as the Federal On-Scene Coordinator of the *Exxon Valdez* oil spill, on shoreline treatment in 1990 and beyond. Other objectives unfolded as the study progressed, including: 1) providing a physical and chemical framework for sites included in NOAA's biological monitoring program; 2) monitoring the effectiveness of certain countermeasures, such as berm relocation; and 3) gaining a better understanding of the processes of oiling and natural cleansing of gravel beaches.

Among the original stations were three sites (stations N-5, N-6, and N-13; Figure 1-1) that had been set-aside (not treated) for research on comparisons of the environmental effects and oil persistence on untreated shorelines with those that had been treated. The intertidal zones of the other stations were treated with one or more of the following techniques: hot-water flushing; nutrient addition; manual removal; berm relocation; and sediment tilling.

The shoreline surveys were repeated up to twelve times over the period September 1989 to August 1992. Whereas Prince William Sound is a relatively sheltered area, at least in comparison with the open north Pacific Ocean, the more exposed sites are subject to significant wave action during the passage of frequent extratropical cyclones. There are also many areas in Prince William Sound that are completely sheltered from significant wave action. The study sites were chosen to represent the entire spectrum of hydrodynamic energy levels that exist throughout the Sound. Shoreline environments studied include: exposed cobble/ boulder platforms with berms; bayhead beaches with mobile fine-gravel, pebble beach/ tidal flat areas; sheltered rubble slopes; and sheltered bedrock. All of these types of shoreline were heavily oiled during the spill.

Results based on the surveys conducted through August 1991 have been presented elsewhere (Michel et al., 1990; Michel and Hayes, 1991; Michel et al., 1991; and Michel and Hayes, 1992). This report synthesizes the data collected during the survey of August 1992 with the earlier results.

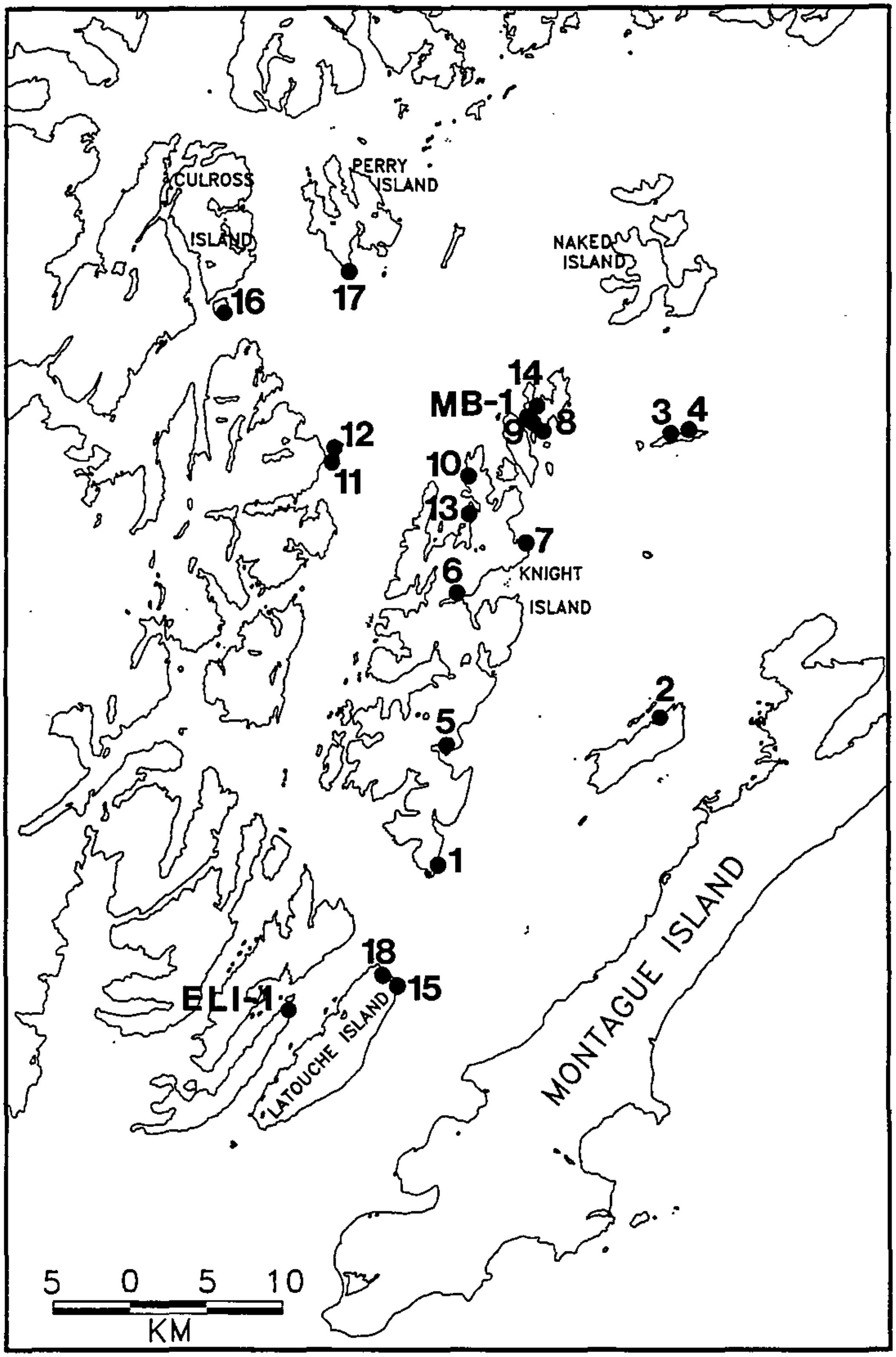


Figure 1-1. Location of permanent stations surveyed as part of NOAA's geomorphology/ chemistry monitoring program between September 1989 and August 1992.

CHAPTER 2
METHODS OF STUDY

A detailed description of the methods of study used on this project is given in Michel and Hayes (1991). The field area has been visited 12 times to date during the project, the first time in September 1989 and the last in August 1992. Table 2-1 lists the stations monitored during each survey.

Field visits to the study sites were planned to coincide with maximum spring low tides. All field surveys were conducted within the window of 2.5 hours on either side of low tide. During each site visit, a topographic profile was run perpendicular to the beach, and details of the morphology, sediments, and surface oil distribution patterns were noted at each interval. The station was photographed and sketched in detail, highlighting the distribution of oil, if present, and the effects of cleanup. Trenches were dug at intervals along the profile to determine the depth of oil penetration. Each trench was described and photographed in detail.

Samples were collected of both surface and subsurface oil contamination, usually oiled sediments. Surface oiled sediment samples, the top two cm, were collected only for detailed characterization and analysis of weathering trends. Subsurface oiled sediment samples were collected from discrete intervals, frequently from the bottom of the oiled sediments in the trench. Other intervals were collected as appropriate. No samples were composited; all samples were grab samples. Sixteen samples were collected during the August 1992 survey.

To date, over 800 samples have been analyzed for total petroleum hydrocarbons (TPH). Over 100 samples have been characterized chemically by gas chromatography/mass spectroscopy (GC/MS) to track weathering patterns in the persistence of polynuclear aromatic hydrocarbons (PAHs). Chemical analyses were carried out by the Environmental Studies Institute, LSU. TPH was determined gravimetrically after solvent extraction with freon (Standard Method 503). Table 2-2 lists the samples collected, the visual descriptions of oiling as recorded in the field, and the TPH and total PAH results in milligrams per kilogram (mg/kg). Sixteen samples were also analyzed by GC/MS; the results for individual PAHs are listed in Appendix 1 and a more detailed analysis of the oil weathering trends is presented in Henry et al. (In Press).

Table 2-1. Listing of the survey dates and stations visited during the NOAA geomorphological/chemical monitoring program.

	1989				1990						1991		1992
Station Number	16-20 Sept.	17-23 Oct.	3-9 Nov.	3-8 Dec.	1-6 Jan.	30 Jan.- 3 Feb.	28 Feb.- 5 Mar.	23-31 May	22-23 June	1-8 Sept.	19-25 Jan.	25-29 Aug.	10-16 Aug.
N-1	X	X	X	X	X	X		X		X	X	X	X
N-2	X	X	X		X	X		X		X			
N-3	X	X		X	X	X	X	X		X	X	X	X
N-4	X	X		X	X	X	X	X		X	X	X	
N-5	X	X		X	X	X		X		X		X	
N-6	X	X			X			X		X		X	X
N-7	X	X		X	X	X		X		X	X	X	X
N-8	X	X	X	X	X	X	X						
N-9	X	X	X		X	X	X		X	X	X		X
N-10	X	X	X	X	X	X	X	X		X	X	X	X
N-11	X	X	X		X	X	X	X		X	X	X	X
N-12	X	X	X		X	X	X	X		X	X	X	X
N-13	X	X	X	X	X	X	X	X		X	X	X	X
N-14	X	X		X		X		X		X	X		X
N-15	X	X	X	X	X	X		X	X	X	X	X	X
N-16	X		X	X		X			X				
N-16Y									X				
N-17	X		X	X		X				X	X	X	X
N-18	X	X	X	X	X	X		X		X	X	X	X
Shelter Bay										X			
Crab Bay										X			
Sheep Bay										X			
Bass Harbor										X			
ELI-1 (Elrington Island)													X
Mussel Beach													X
Outside Prince William Sound													
PD-1								X					
US-5								X					
YG-2								X					
PB-1								X					

Table 2-2. Sediment samples collected for chemical analysis during the August 1992 survey.

Station No.	Zone[1]	Depth (cm)	Visual Oil[2] Description	TPH (mg/kg)	Total PAH (mg/kg)
N-1	TR B, Upper platform	40-55	MOR	13,960	109
N-1	Storm berm	0	ST/CT	3,460	3.5
N-3	TR A, Upper platform	35-42	MOR	8,150	11
N-3	TR B, Upper platform	15-25	MOR	12,420	25
N-7	TR A, Upper platform	25-40	MOR	14,700	30
N-7	TR B, Upper platform	35-45	MOR	18,710	36
N-7	TR C, Upper platform	35-45	MOR	15,870	36
N-9	TR F, Tidal flat	0-10	OF	430	0.1
N-10	TR A, Beachface	25-30	MOR	4,680	5.9
N-10	TR A, Beachface	30-40	MOR	1,550	6.4
N-11	TR A, Beachface	0-5	MOR	10,190	23
N-13	TR A, Upper rubble	15-25	MOR	7,720	15
N-13	TR B, Upper rubble	15-25	OF	150	0.1
N-15	TR C, Upper platform	10-15	MOR	6,640	5.1
N-17	TR A, Central ramp	5-15	ST/CT	6,040	10
ELI-1	TR E, Central ramp	10-15	AP	13,640	58

1 Zones refer to geomorphology of the beach profile, as described in the text. TR = trench.

2 MOR = medium oil residue; LOR = light oil residue; OF = oil film; AP = asphalt pavement; CT = coat; ST = stain.

Throughout the text of this report, the terminology and definitions used are those established during the 1991 interagency shoreline surveys of the oiled regions (MAYSAP). Surface oil was described using the following terms:

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

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

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

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

Subsurface oil was described using the following terms:

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

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

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

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

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

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

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

CHAPTER 3
RESULTS OF AUGUST 1992 SURVEY

INTRODUCTION

The August 1992 survey was different from previous surveys in two ways. First, a chemist from LSU joined the team, as part of a special project being conducted jointly with LSU to characterize the chemical weathering of residual oil in Prince William Sound 3.5 years after the spill. A detailed plan was developed to collect samples from the various environments in Prince William Sound, ranging from oil stain on bedrock, to mousse in crevices, to subsurface oil in gravel beaches. A key component of the plan was the coordination of sampling with the geomorphological studies, so that the physical setting and weathering processes would be included in the sampling strategy and interpretation of the results. Three to five samples from each microenvironment were collected.

Second, it was likely that this survey would be the last time that all stations would be part of the annual monitoring. NOAA is committed to a ten-year monitoring program in Prince William Sound, but some stations will have to be surveyed on a less-frequent period. We wanted to "close-out" some stations with a final survey that would include as much detailed observations and documentation as possible. We also established new front or back stakes at many sites, to replace those lost during cleanup activities and storms, or inadvertently removed by other groups. All of the signs marking the sites have been removed; detailed sketches were made so the stations can be readily located in the future.

The results of the August 1992 survey of each station are presented in this report, so that the record of the observations for the period is complete. However, we also have summarized the trends at these stations and discussed the most important points from previous reports. Although this report is complete in and of itself, we recommend that the reader be familiar with two previous reports, which completely characterize each site for the period September 1989 to January 1991 (Michel and Hayes, 1991), and present the changes observed during the August 1991 survey (Michel and Hayes, 1992). At the end of this report, we present several models for the behavior and fate of shoreline oil, based on the shoreline types included in our monitoring program.

COBBLE/BOULDER PLATFORMS WITH BERMS

Introduction

Six of the stations revisited during this survey were originally classified as cobble/ boulder platforms with berms. These areas have been of special concern during the response to the *Exxon Valdez* spill because oil had penetrated deeply into the sediments on all heavily oiled gravel beaches of this class in Prince William Sound. The middle and lower portions of the intertidal zones of these beaches are typically gently sloping surfaces of bedrock overlain by a mixture of granule/sand and pebbles that is covered by a veneer (armor) of cobbles and boulders, which shields the underlying sediments from erosion. The upper part of the beach profile usually contains a high, generally supratidal, storm berm, normally composed of cobbles, which has a series of mobile berms composed of pebbles and cobbles on its seaward face (Figure 3-1). These lower-level berms occur within the upper intertidal zone. All beaches of this class are limited to the segments of the Prince William Sound shoreline most exposed to storm-wave action.

Station N-1 (Point Helen)

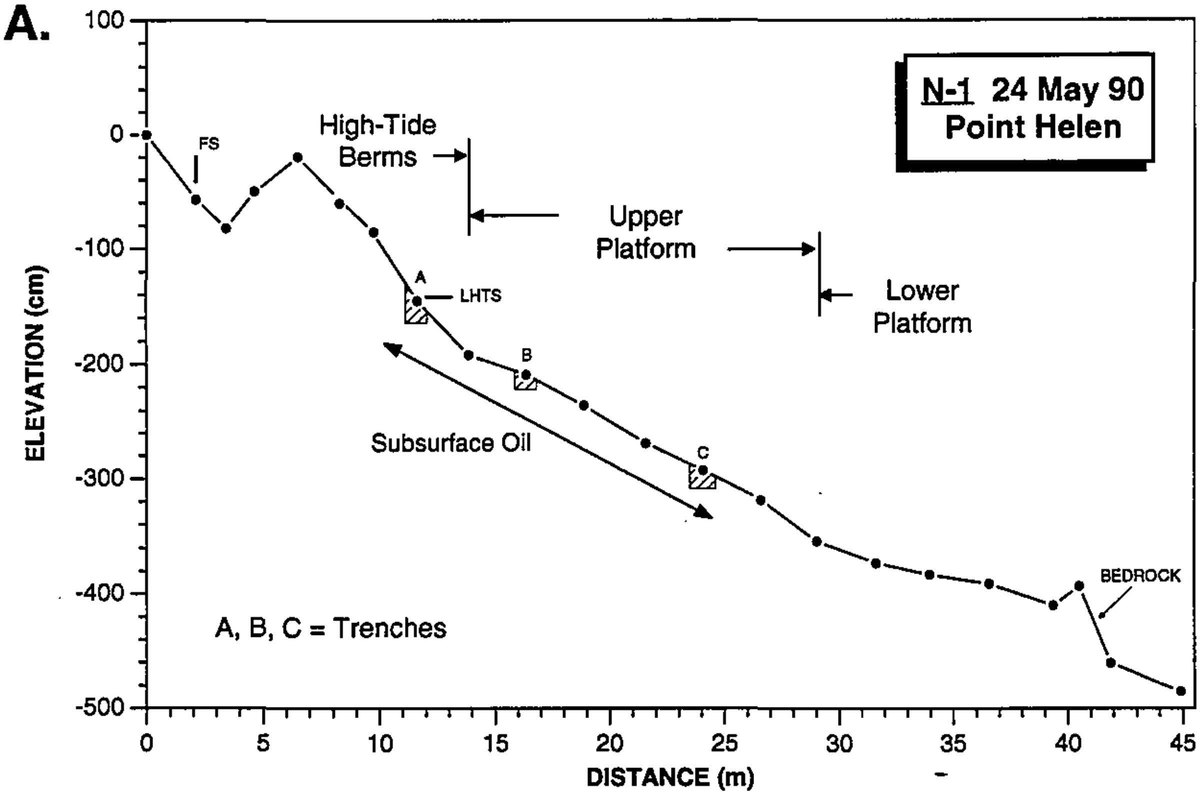
Introduction. Station N-1 is located a little over 1.5 kilometers (km) north of the southern tip of Knight Island at Point Helen. The permanent beach profile at station N-1 is located 150 meters (m) north of a prominent raised sea stack that is located in the middle of the intertidal zone. This part of Knight Island was uplifted 2.5 m during the Good Friday earthquake of 1964.

Figure 3-1. (Facing Page) Station N-1 (Point Helen; Knight Island).

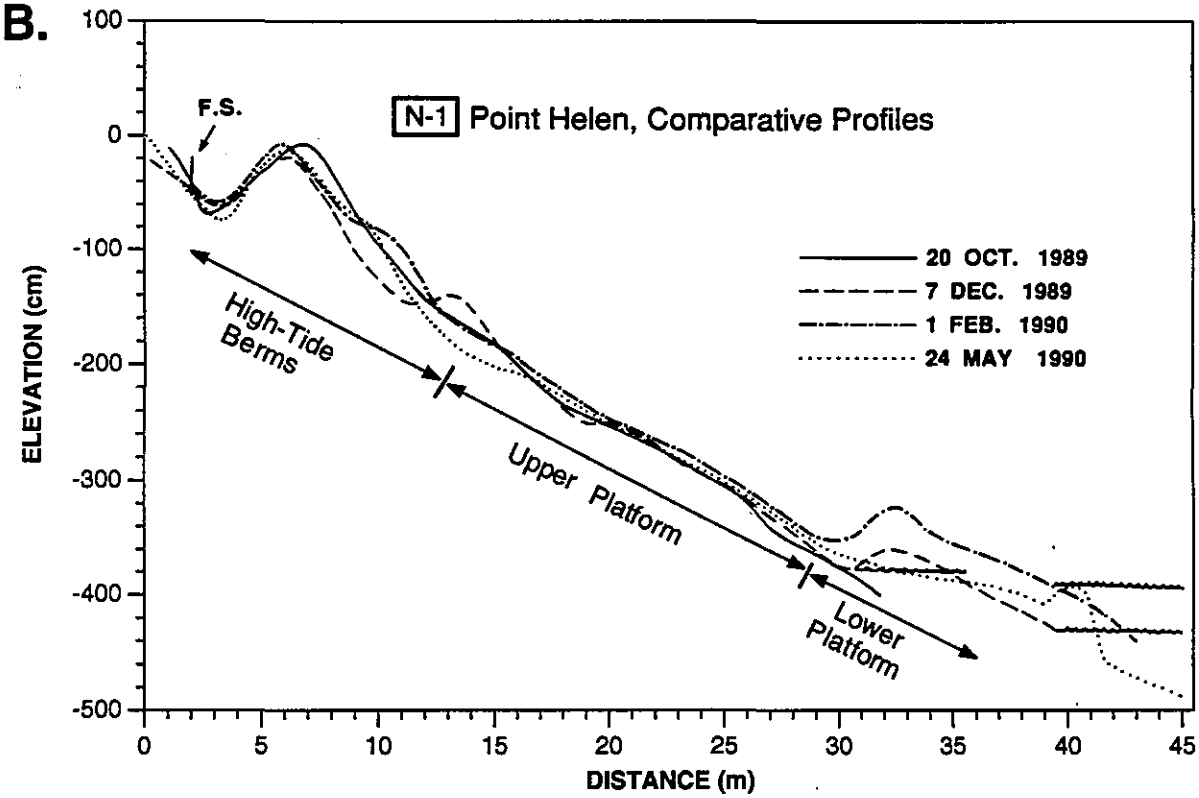
A. Topographic profile surveyed on 24 May 1990 showing morphological subdivisions and location of trenches dug on that date.

B. Changes in the beach profile between September 1989 and May 1990. Note the erosional/depositional patterns at the high-tide berms, the relative stability of the upper platform, and the presence of migrating swash bars on the lower platform. (From Michel et al., 1991; Figure 4.)

A.


N-1 24 May 90
Point Helen
High-Tide Berms
Upper Platform
Lower Platform
FS
LHTS
A
B
C
Subsurface Oil
BEDROCK
A, B, C = Trenches
ELEVATION (cm)
DISTANCE (m)

B.


N-1 Point Helen, Comparative Profiles
F.S.
20 OCT. 1989
7 DEC. 1989
1 FEB. 1990
24 MAY 1990
High-Tide Berms
Upper Platform
Lower Platform
ELEVATION (cm)
DISTANCE (m)

This station is one of the more exposed (to wave action) of our study sites, with an effective fetch distance of 15 to 20 km to the east and 45 to 50 km to the north-northeast. Wind data collected at Lone Tree, Seal, and Danger Islands in Prince William Sound for the storm season of 1989/1990 show that storm winds in the Sound blow overwhelmingly out of the north and northeast (discussed by Michel and Hayes, 1991).

Morphology and sediments. The general morphology of station N-1, which has been surveyed eleven times to date, is illustrated in Figures 3-1 and 3-2. A prominent gravel storm berm was present at the landward edge of the beach during the earlier surveys (Figures 3-1A and 3-2A). As shown by the multiple beach-profile plots in Figure 3-1B, the middle portion of the profile, the upper platform, has been quite stable over time. On the other hand, numerous intertidal gravel bars, called swash bars, have moved across the lower platform during the study period. Our data show that the maximum vertical changes in the profile due to erosion/deposition cycles developed for this station have been 30 to 40 cm for the migrating swash bars and 50 to 60 cm for the erosional/depositional episodes at the high-tide berms.

As the sequential beach-profile plots of Figure 3-1B show, beach sediments at N-1 are frequently moved around by wave-generated currents during the storm season, and even to some extent during the summer months. The gravel is moderately well-sorted, and individual cobbles and boulders are subround to round (discussed in detail by Michel and Hayes, 1991). As a generalization, the concentration of pebbles has been greatest in the zone of high-tide berms, cobbles predominated on the upper platform

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Figure 3-2. (Facing Page) Changes at station N-1 (Point Helen; Knight Island). All views look north.

A. 20 October 1989. Person is standing on crest of recently activated storm berm. Photograph by D. Hall.

B. 27 August 1991. Area of former storm berm that had been planed-off during the berm-relocation project carried out earlier in the summer. Compare with photograph in A and field sketches in Figure 3-4.

C. 13 August 1992. Arrow points to new high-tide berm developed on offshore side of the planed-off area. Compare with sketches in Figure 3-4.

A.

B.

C.

(with boulders increasing in an offshore direction), and boulders made up more than 50 percent of the surface sediments of the lower platform. Examination of over 30 trenches dug at this site shows that a surface armor has developed over the underlying sediments of the upper and lower platforms. Data collected in May 1990 show that, in places, the mean clast size of the surface armor may be four times as great as that of the underlying sediments (e.g., 16 cm vs. 4 cm). Armoring forms as a result of selective removal of small- and intermediate-sized gravel from the surface layer by the intense wave-generated currents typical of that part of the beach profile (Michel and Hayes, 1991; Hayes et al., 1991).

The beach at station N-1 experiences the strongest longshore sediment transport rates of any of the stations studied, because of the oblique orientation of the shoreline relative to the dominant northerly and northeasterly winds. Some of the more striking lines of evidence supporting this conclusion are: 1) abundance of intertidal swash bars, particularly in the lower intertidal zone, which have a strongly oblique orientation to the beach and slip faces that slope to the south; 2) striking asymmetry of high-tide berms in the form of rhythmic topography moving south; and 3) clear grain-size trends from coarse to fine in a southerly direction.

Berm relocation. A major berm-relocation project was carried out along this segment of the Knight Island shoreline in the summer of 1991. Because of the presence of some persistent zones of subsurface oil, the prominent storm berm along 2,000 m of shoreline was planed-off flat, exposing the oiled sediments, with some removal of heavily oiled sediments. Some of the excavated sediment was pushed onto the upper platform. Station N-1 was situated within the area where the storm berm was relocated. Figure 3-2 shows a series of photographs of the high-tide berms taken prior to, just after, and one year after the berm-relocation project. Note that, as of August 1992, the storm berm showed no evidence of recovery, although the relocated sediments were being worked into high-tide berms on the beachface. The beach profiles at N-1 surveyed in January and August 1991, presented in Figure 3-3, illustrate the changes resulting from planing off the storm berm. The oblique field sketch in Figure 3-4A illustrates the character of the beach a few weeks after the berm-relocation project was completed.

We believe that complete removal of the storm berm, as was done at Point Helen, has some inherent problems, including:

1) **The length of time it may take the beach to recover to its original profile.** A resurvey of the site over one year after the berm relocation, carried out on

13 August 1992 revealed that the storm berm was far from completely recovered. As shown by the profile plots in Figure 3-3B and the field sketch in Figure 3-4B, by August 1992, the strong wave-dominated longshore currents that prevail in this area had remolded the sediments on the exposed side of the planed-off surface into a series of low-level depositional berms, oriented obliquely to the northeast wave approach direction (rhythmic topography), but the storm berm had not recovered. The comparison of surface grain size along the profile well before (May 1990), soon after (August 1991), and one year after (August 1992) the berm relocation (see Figure 3-5) shows that the surface sediment distribution disrupted by the berm-relocation project had not recovered to its original pattern. A cover of pebbles still dominated the upper half of the profile in August 1992.

2) **Aesthetic impairment of the beach for a long time.** Disarray of logs and boulders behind the planed-off berm was particularly notable through August 1992.

3) **Exposure of areas behind the original storm berm to potential erosion.** Beach erosion is a problem of more concern in developed areas than in Prince William Sound, but one that could definitely affect the usefulness of this technique at other spills.

Surface oil. At the time of the September 1989 survey, as much as 50 percent of the beach surface at station N-1 was covered with oil from the spring berm to the upper platform, with the offshore edge of surface oil coverage occurring at the major rock outcrop on the lower platform (Figures 3-1A and 3-4). During the first major winter storm after the spill, which occurred in mid-October 1989, oily debris was pushed over and behind the storm berm and under log piles. As shown in Table 3-1, the maximum surface oil reading recorded for any gravel beach station during the May 1990 survey was the 100 percent recorded at N-1. This high value was noted for the heavily oiled debris that had remained behind the protective barrier of the storm berm throughout the storm season. Surface oil in the intertidal zone at N-1 declined steadily until only a trace of stain remained at the upper intertidal zone as of September 1990. A high reading of 75 percent surface oiling was recorded during the August 1991 survey, as the result of exposure of previously subsurface oiled clasts on the surface during the berm-relocation project. During the 13 August 1992 survey, we still found surface coat readings as high as 50 percent in the debris on the landward side of the area planed-off during the berm-relocation project in the summer of 1991 (Table 3-1; Figure 3-4B).

Subsurface oil. A summary of the interval and degree of subsurface oil as observed in trenches dug along the profile since September 1989 is listed in Table 3-2 and showed graphically in Figure 3-6. Several conventions are used in these summaries which require explanation:

1) The trench data are grouped by geomorphological zone. Figure 3-1 shows the contacts of the three zones at N-1. It should be noted that the exact location of trenches in each zone varied somewhat during each survey. When two different trenches are included for the same zone, they are shown on the same line and separated by a slash.

2) The depths are recorded as relative to the mean sediment surface, which does not include the parts of cobbles and boulders that protrude above the surface.

3) A plus symbol (+) is used to indicate that clean sediments were not reached at the bottom of the trench. Many times water filled the trenches, making it difficult to determine degree of oiling of the sediments below the water table. Where these data are plotted, such as in Figure 3-6, the bottom-of the oiling may be inferred from other trenches, which is indicated by dashed lines.

4) Degree-of-oiling categories were assigned based on field observations, correlated with TPH as measured for selected intervals. The vertical contacts between oiling degrees were drawn as sharp breaks, although it is realized that, in many cases, changes in degree of oil contamination are gradual, especially for the early surveys. Over time, reworking of sediments did produce sharper contacts between degrees of oiling. Temporal changes in

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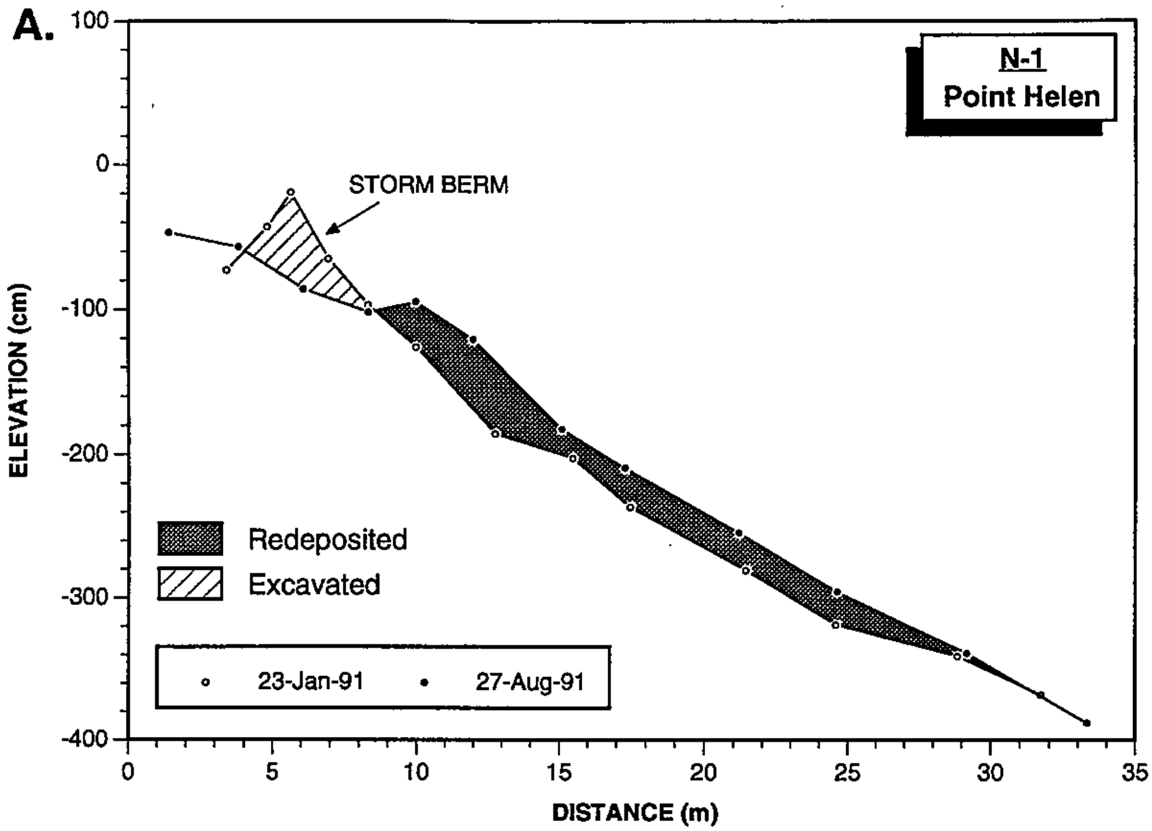
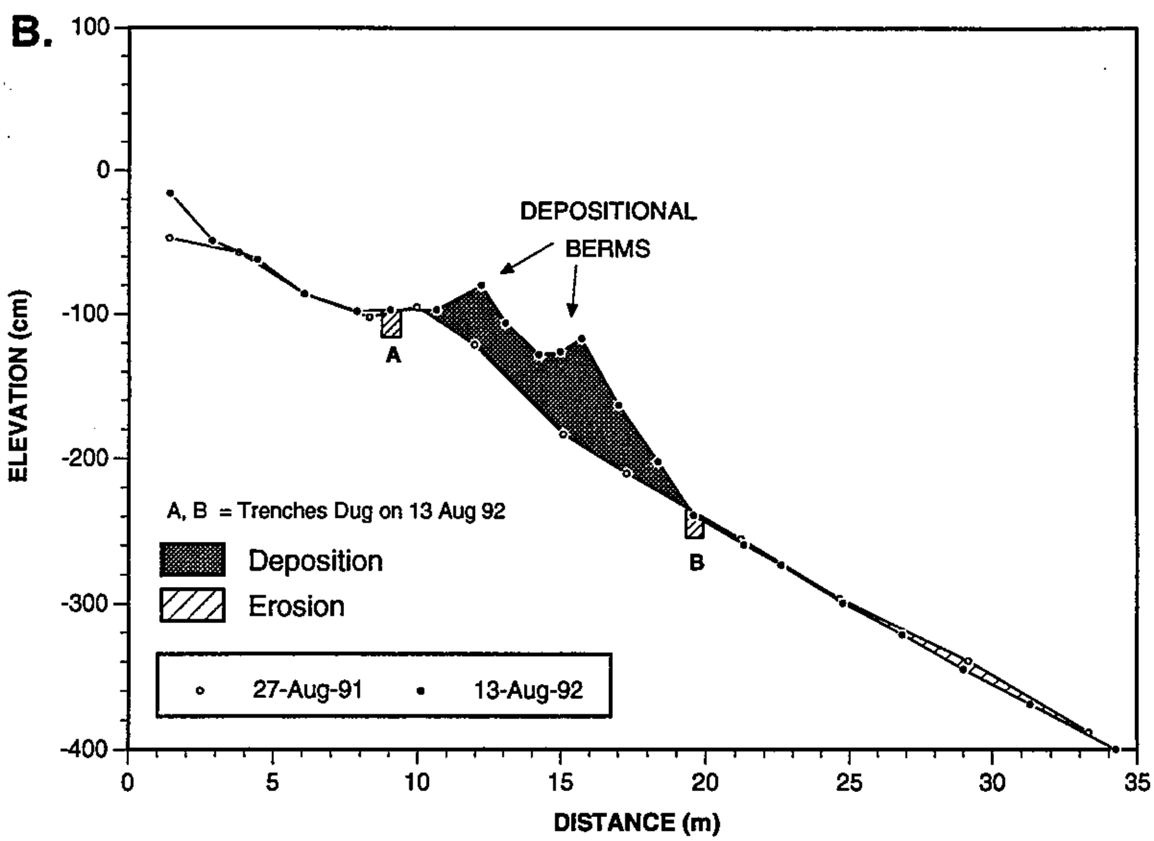
Figure 3-3. (Facing Page) Topographic beach profile changes at station N-1 (Point Helen) that illustrate the following:

A. Relocation of storm berm sediments in summer of 1991.

B. Recovery of lower-level depositional berms one year after berm relocation. The permanent markers at station N-1 were destroyed during berm-relocation processes in the summer of 1991. Therefore, these overlays, though close, are only approximations.


A.
N-1
Point Helen
STORM BERM
ELEVATION (cm)
DISTANCE (m)
Redeposited
Excavated
23-Jan-91
27-Aug-91


B.
DEPOSITIONAL
BERMS
A
B
A, B = Trenches Dug on 13 Aug 92
ELEVATION (cm)
DISTANCE (m)
Deposition
Erosion
27-Aug-91
13-Aug-92

oiling are also connected, drawn as straight lines between two points with no effort made to change the slope, show a gradual change, or indicate a sudden change related to a storm event.

5) Only the oiled intervals are shown in the tables. That is, if the top 16 cm in a trench are clean, with 16 to 40 cm of light oil residue, and clean sediments were not reached at the bottom of the trench, then the data for that month would be entered as 16-40+ (LOR).

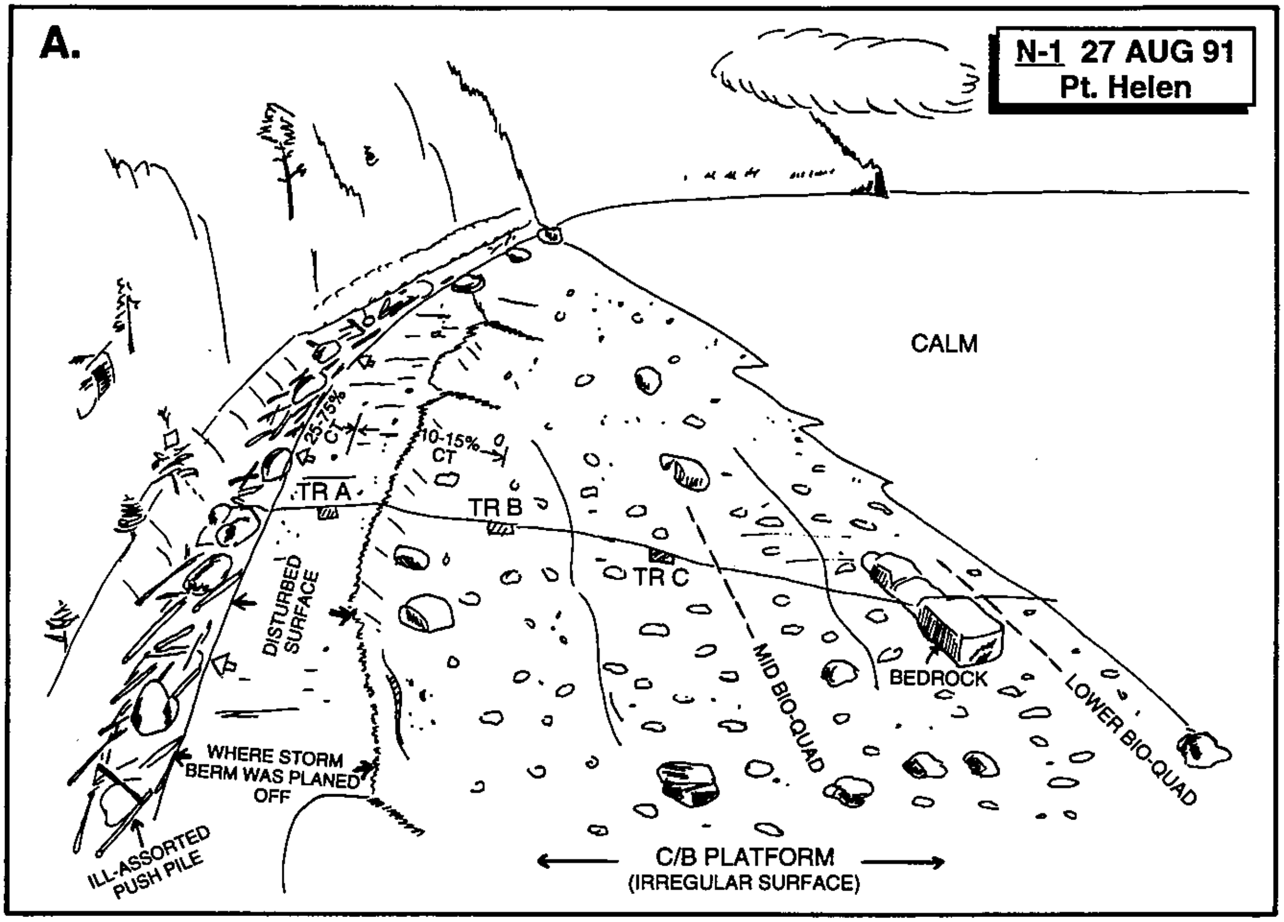
The subsurface oil distribution over time at N-1 shows a classic pattern. This pattern is discussed first for the high-tide berms (Figure 3-6A). By the end of the 1989 summer, MOR (2,000-5,000 mg/kg oil) extended from the surface to at least 48 cm at the high-tide berms (other studies at Point Helen showed oil penetration to more than 100 cm). By December 1989, the formation of new high-tide berms piled 15 cm of lightly oiled sediments on top of the oiled zone (see Figure 3-1 for comparative plots of the beach profile). Continued reworking of the surface sediments (to about 25 cm depth) by the deposition and erosion of berms is evidenced by the decrease in shallow oil content to just a stain on the cobbles by February 1990, then to no visible oil by September 1990. The deeper oil was MOR and changed little until the September 1990 survey, when only light oiling (<2,000 mg/kg) was observed. After the major storm-berm relocation project in the summer of 1991, only oil films on the cobbles and pebbles were observed. The berm relocation was effective at reducing the subsurface oil in this zone, though it is noted that, at N-1, the levels had been already reduced significantly.

Figure 3-4. (Facing Page) Field sketches of station N-1 (Point Helen). Compare with photographs in Figure 3-2.

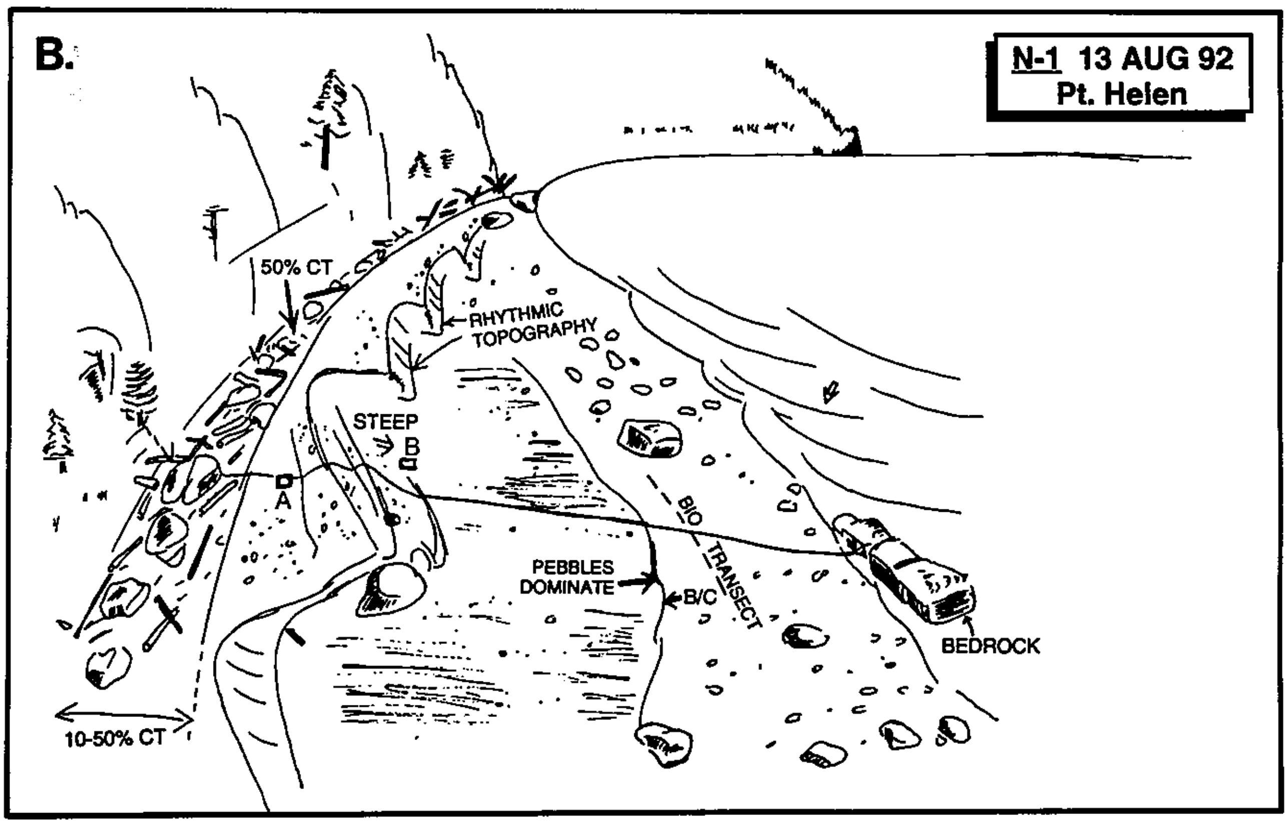
A. 27 August 1991. Note planed-off nature of the storm-berm area resulting from berm-relocation project.

B. 13 August 1992. Rhythmic topography has developed along exposed face of planed-off area.

A.


N-1 27 AUG 91
Pt. Helen
CALM
25-75% CT
10-15% CT
TR A
TR B
TR C
DISTURBED SURFACE
MID BIO-QUAD
LOWER BIO-QUAD
BEDROCK
WHERE STORM BERM WAS PLANED OFF
ILL-ASSORTED PUSH PILE
C/B PLATFORM
(IRREGULAR SURFACE)

B.


N-1 13 AUG 92
Pt. Helen
50% CT
RHYTHMIC TOPOGRAPHY
STEEP
B
A
BIO TRANSECT
PEBBLES DOMINATE
B/C
BEDROCK
10-50% CT

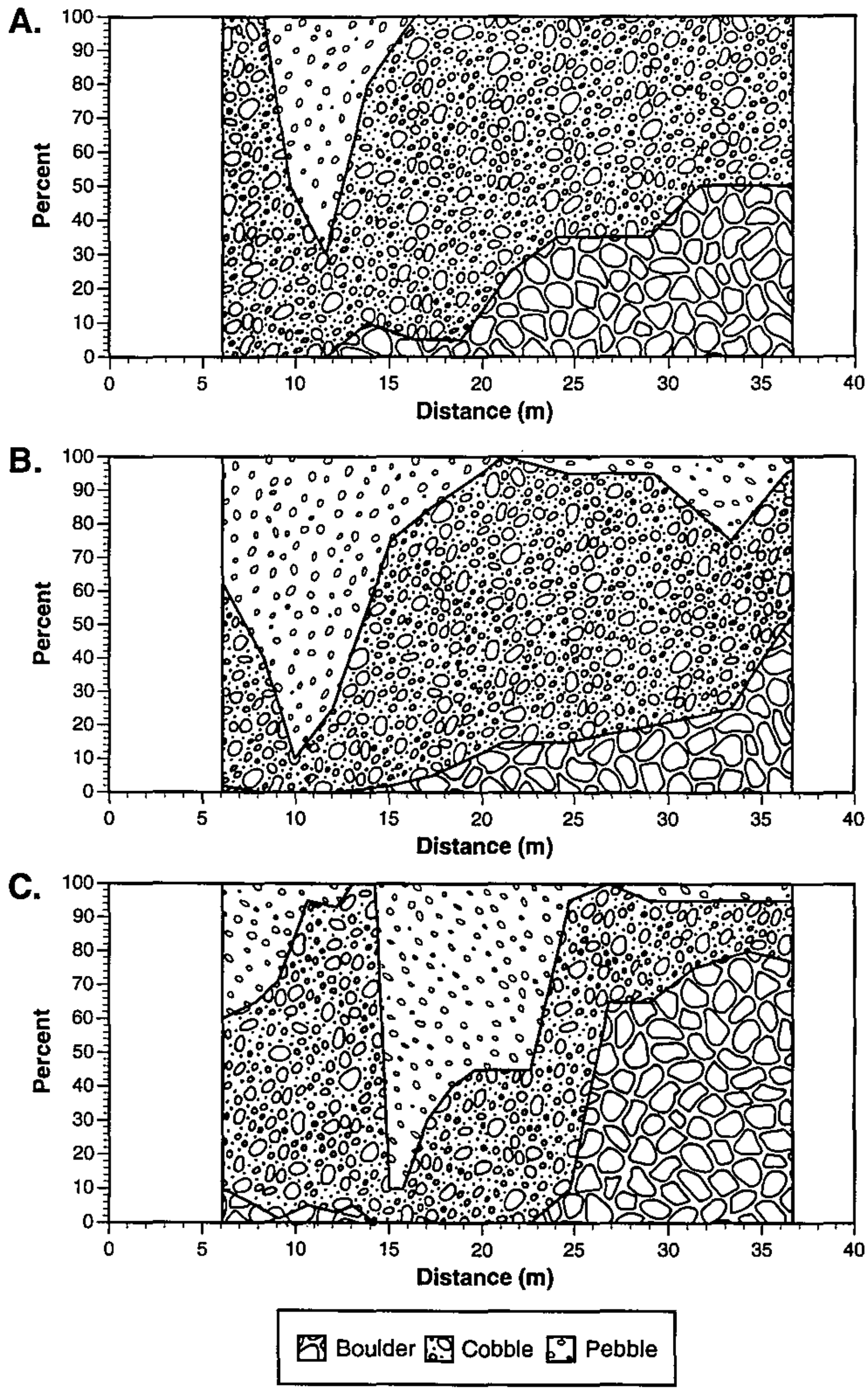


Figure 3-5. Distribution of surface sediments within the intertidal zone of station N-1 (Point Helen), based on visual estimates at each survey point along the profile: (A) 24 May 1990, (B) 27 August 1991, and (C) 13 August 1992.

Table 3-1. Maximum surface oiling observed on gravel beach profile (in percent).

Station	September 1989	May 1990	August 1991	August 1992
N-1	95	100	75*	50
N-3	100	20	5	0
N-4	75	0	0	-
N-7	80	5	0	0
N-14	90	5	-	0
N-15	100	15	60*	1
N-17	70	0	0	0
N-18	100	5	50*	0

* Site of major berm relocation/excavation project.

Table 3-2. Historical summary of the interval and degree of subsurface oil at station N-1 (Point Helen). Depths are reported in centimeters.

Survey Date	High-tide Berms	Upper Platform	Lower Platform
Oct. 1989	0-48+ (MOR)	0-50+ (MOR)	
Dec. 1989	0-15 (LOR) 15-54+ (MOR)	0-25+ (LOR)	
Feb. 1990	0-25 (ST) 25-45+ (MOR)	0-34+ (LOR)	
May 1990	0-14 (ST) 14-34+ (MOR)	16-40+ (LOR)	
Sept. 1990	18-38+ (LOR)	22-38 (LOR) 38-48+ (MOR)	
Jan. 1991	22-52+ (LOR)	20-26+ (ST)/0-40 (No oil)	
Major berm-relocation project—summer 1991			
Aug. 1991	0-55 (OF)	30-65 (MOR)/35-75+ (LOR) 65-72+ (HOR)	
Aug. 1992	19-64+ (OF)	42-60 (MOR/HOR)	

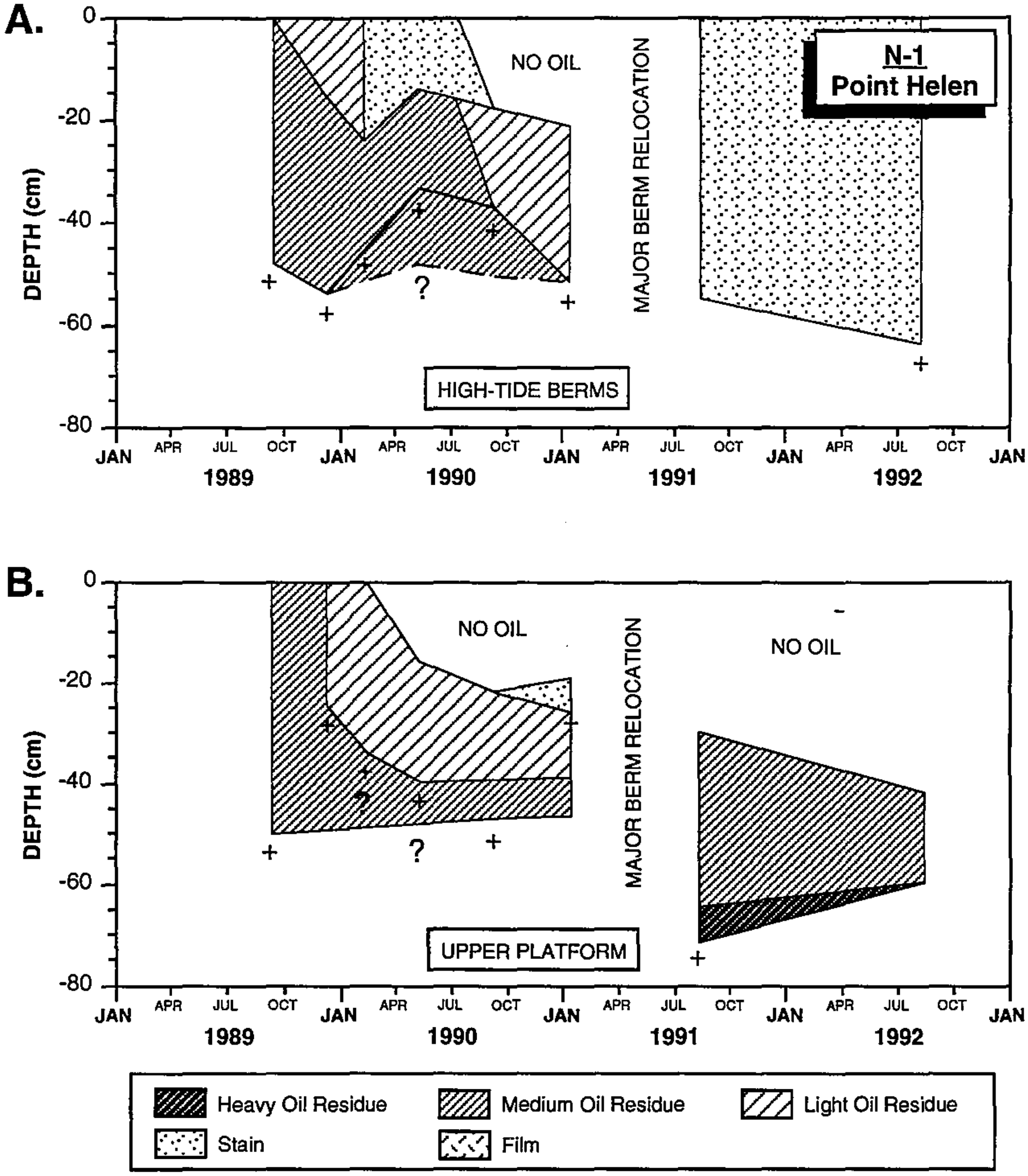


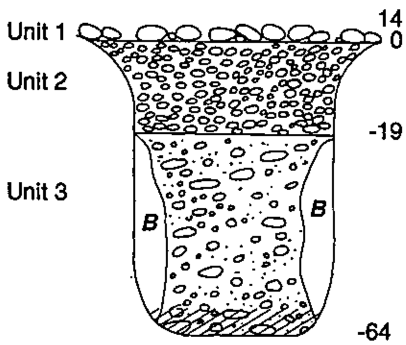
Figure 3-6. Time-series plot of the interval and degree of subsurface oil at station N-1 (Point Helen), based on trench descriptions and chemical analyses, for the (A) high-tide berms and (B) upper platform. See text for explanation of conventions used.

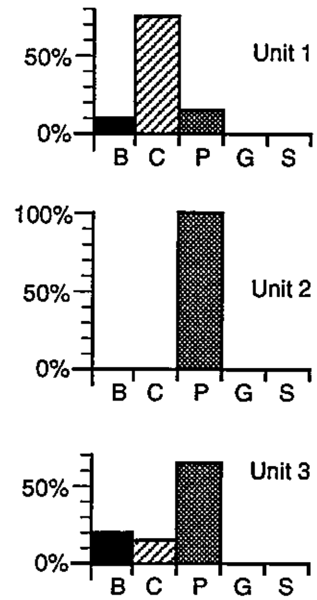
A somewhat different pattern can be seen for the subsurface oil in the upper platform (Figure 3-6B). Subsurface oil extended throughout the upper platform, but not to the lower platform (see Figure 3-1A for these zones). The sediments on the upper platform are not frequently reworked, so it took longer for oil concentrations to decrease. It is important to note that as of summer 1990, the top 20 cm on the upper platform were free of oil, and the moderate oiling was restricted to depths below 38 cm.

By the time of the August 1991 survey, the pile of relocated sediment on the upper platform had been reworked to the point that all visible oil was gone. But the original subsurface oil layer was unchanged, and a layer of heavily oiled sediments (over 12,000 mg/kg oil) was reached at over 70 cm depth. By August 1992, there was again little change in the extent or degree of this subsurface oil (13,960 mg/kg), which remained well buried deep (40 cm) beneath the newly formed berms (see Figure 3-3B). Therefore, the berm relocation may have slowed the weathering of the subsurface oil in the upper platform. Figure 3-7 shows the detailed trench descriptions made during the August 1992 survey; the locations of these trenches are shown in the field sketch in Figure 3-4B. Note the deep subsurface oil in trench B. Figure 3-8 shows photographs of trench B (on the upper platform), which was dug in August 1992, illustrating the oiled interval of 42-60 cm described as MOR. The sample collected from the interval of 40-55 cm contained 13,960 mg/kg, essentially no different than 1991. This deeply buried oil was also among the least weathered, as discussed in Chapter 5. Figure 3-8B is a close-up photograph of sediment dug from the lower part of the trench, where the oiling was close to being HOR.

N-1 POINT HELEN, 13 AUGUST 1992

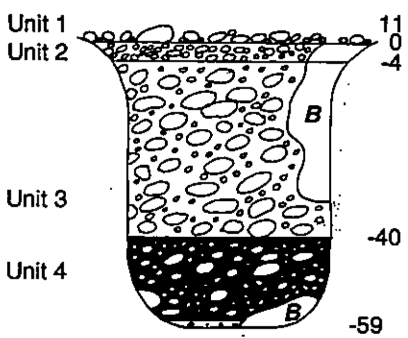
TRENCH A

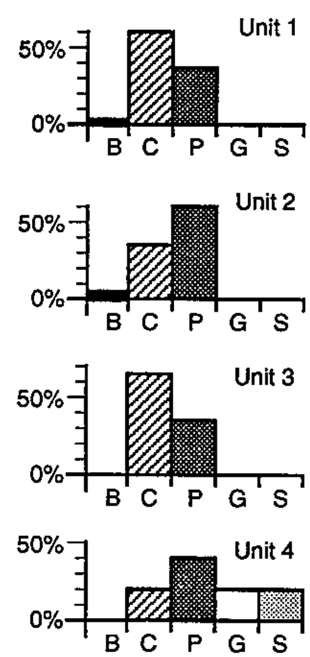




Unit 1: (B/C/P) armor; 14 cm thick.
Unit 2: No oil; layer of pebbles; 19 cm thick.
Unit 3: (B/C/P) unit; 45 cm thick; oil film (VLOR) 55-64+ cm (did not reach the bottom of the oil layer).

TRENCH B





Unit 1: (B/C/P) armor; 11 cm thick.
Unit 2: No oil; layer of pebbles beneath surface armor; 4 cm thick.
Unit 3: No oil; layer of cobbles/pebbles; 36 cm thick.
Unit 4: (MOR) 42-53; (HOR) 53-58; "clean" below.

Figure 3-7. Descriptions for the two trenches dug at station N-1 (Point Helen) on 13 August 1992. Note presence of heavy oil at depths below 42 cm in trench B.

Station N-3 (Smith Island)

Introduction. This station, which has been surveyed 11 times since the first survey in 1989 (Table 2-1), is located in a small indention on the northwest side of Smith Island. A short distance (±50 m) west of the survey line, the shoreline turns abruptly to the south. As shown on the oblique aerial photograph and field sketch in Figure 3-9, two prominent bedrock outcrops west of the profile create a natural groin effect, trapping sediment being transported to the west along the beach and allowing it to accumulate in the area of station N-3. Consequently, a relatively thick layer of gravel has been deposited on top of the underlying bedrock platform, which was uplifted 1.5 m during the 1964 earthquake.

The effective fetch at this site is around 10 to 12 km to the north; however, a large expanse of open water is located to the north-northeast of the site, a straight-line distance of 45 to 50 km. Thus, this site is one of the more exposed gravel beaches in Prince William Sound.

Morphology and sediments. The morphology of station N-3 is illustrated in detail by the field sketch in Figure 3-9B and the topographic profile plotted in Figure 3-10A. The beach consists of a prominent storm berm with minor spring- and neap-tide berms located on its seaward face. The average beachface slope is 12°, a typical value for gravel beaches. The coarse-grained cobble/boulder platform, which slopes offshore at an average angle of 4.3°, usually contains several well-developed gravel ridges oriented parallel with the water line. As shown in Figures 3-9B and 3-10A, three prominent ridges were present when the profile was surveyed on August 16, 1992. These features, here termed berm-like ridges, are thought to form near the lower three of the four mean levels of stillstand during the tidal cycle in Prince William Sound, which is marked by a strong diurnal inequality: 1) high-high tide; 2) low-high tide; 3) high-low tide; and 4) low-low tide.

Except for an erosional event between 30 January and 4 March 1990 that lowered the whole profile about 40 cm and a berm-relocation project carried out during the summer of 1990 (discussed below), the morphology of this beach has remained quite stable throughout the study period. There was some erosion of the profile during the interval between August 1991 and August 1992, when the beachface was lowered about 40 cm and steepened considerably (Figures 3-9B and 3-10A).

The sediments in the high-tide berms are about equally divided between pebbles and cobbles, and those on the lower and upper platforms are about equally divided between cobbles and boulders. As at station N-1, a surface armor of coarser clasts has formed along the profile, except in the beachface area (Figure 3-10B). The clasts are subround to round, indicating significant abrasion during wave-generated sediment transport.

Berm relocation. As discussed by Michel and Hayes (1992), a berm-relocation project was carried out at this site in mid-July 1990. During the berm-relocation process, the seaward face of the berm was excavated 0.5 to 1.0 m, and the excavated sediment was placed on top of the upper platform. The crest of the storm berm was not changed in the relocation process. By the time of the 12 January 1991 survey, the excavated area had been completely filled-in, and the entire profile had returned to its original configuration. By the time of the 26 August 1991, survey, the surface sediment distribution pattern had resumed the configuration it had before the berm-relocation project.

Surface oil. This station, which was heavily oiled during the spill and cleaned several times in the summer of 1989, showed a slower rate of removal of surface oil than many of the other cobble/boulder platforms with berms. As late as May 1990, there was 5 to 20 percent stain on the surface cobbles (Table 3-1) and an asphalt pavement was exposed on the upper platform. This oil remained despite the occurrence of erosion on the profile, a reflection, perhaps, of the extremely high levels of subsurface oil at this site. As late as August 1991, one year after berm relocation, estimates as high as five percent stain, coat, and splash were recorded for some of the larger clasts on the upper platform. No surface oiling was observed during the August 1992 survey.

Figure 3-8. (Facing Page) Photographs of trench B at station N-1 (Point Helen) on 13 August 1992.

A. The oiled interval (MOR) starts about five cm below the boulder in the left-center of the photograph. The sediments around and above the boulder were visually clean.

B. Close-up of sediments removed from the base of trench B, from the 50-60 cm interval, classified as moderate/heavy oil residue.

A.

B.

Subsurface oil. The trends in the depth and degree of subsurface oil at N-3 are shown in Figure 3-11 and Table 3-3. It should be noted that oil extended to the lower platform through December 1989, with heavy oil found to depths of 25 to 30 cm. At the high-tide berms, reworking of sediments by the building and eroding of spring and neap berms steadily reduced the degree and thickness of oiling. Note that the oiling in the high-tide berms goes from heavy, to moderate, to light in the top 25 cm over the first winter. Below this depth, oil concentrations ranged from 3,300 to 22,700 mg/kg through March 1990. There was a major erosional event between the February and March 1990 surveys removed an estimated 40 to 50 cm from much of the profile and completely eroded the subsurface oil from the lower platform.

In Figure 3-11A, the plot after the berm relocation reflects the removal of at least 40 cm of sediment from the high-tide berms, in effect bringing the MOR to the surface in September 1990. A sample from 25 to 30 cm contained over 7,600 mg/kg oil; thus significant oil remained even in the excavated zone. Subsequently, the excavated sediment was pushed back by wave-generated currents, burying the MOR beneath at least 40 cm of oil-stained cobbles and pebbles, as found in January 1991.

The trend in subsurface oil in the upper platform was very different (Figure 3-11B). The sediments were heavily contaminated (containing up to 47,800 mg/kg in 1989) to more than 60 cm. Through 1990, concentrations ranged from 4,000 to 16,300 mg/kg, with little differences with depth in each trench. The 44 cm of stained sediments in this zone in September 1990 reflects the piling of excavated sediments on top of the original oil. By January 1991, the HOR was exposed again as the sediment pile was returned to its previous position. It was not until the August 1991 survey that significant erosion of the HOR from the upper platform was observed. At last, the top 22 cm were visibly free

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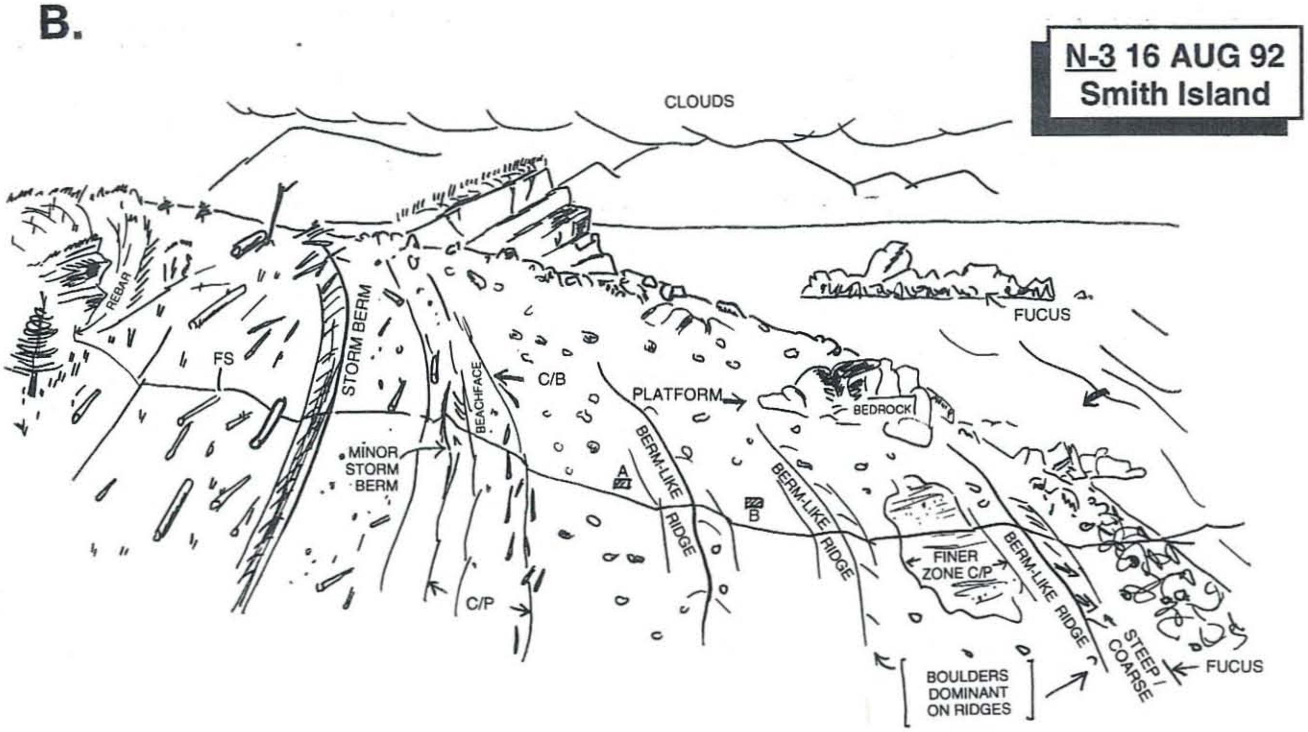
Figure 3-9. (Facing Page) Station N-3 (Smith Island).

A. West-looking aerial view on 25 May 1990. Line indicates approximate location of beach profile. Large rocks west of the profile act as natural groin to trap east-to-west moving sediments.

B. Field sketch drawn on 16 August 1992. Note well-developed berm-like ridges.

A.

B.


N-3 16 AUG 92
Smith Island
CLOUDS
REBAR
FS
STORM BERM
MINOR STORM BERM
BEACHFACE
C/B
C/P
PLATFORM
BERM-LIKE RIDGE
BEDROCK
A
B
BERM-LIKE RIDGE
FINER ZONE C/P
BERM-LIKE RIDGE
STEEP / COARSE
FUCUS
FUCUS
BOULDERS DOMINANT ON RIDGES

of oil, and there was a 10 cm zone of MOR. There must have been strong storm waves from the north in the latter half of the 1990/1991 storm season that reworked the sediments to these depths.

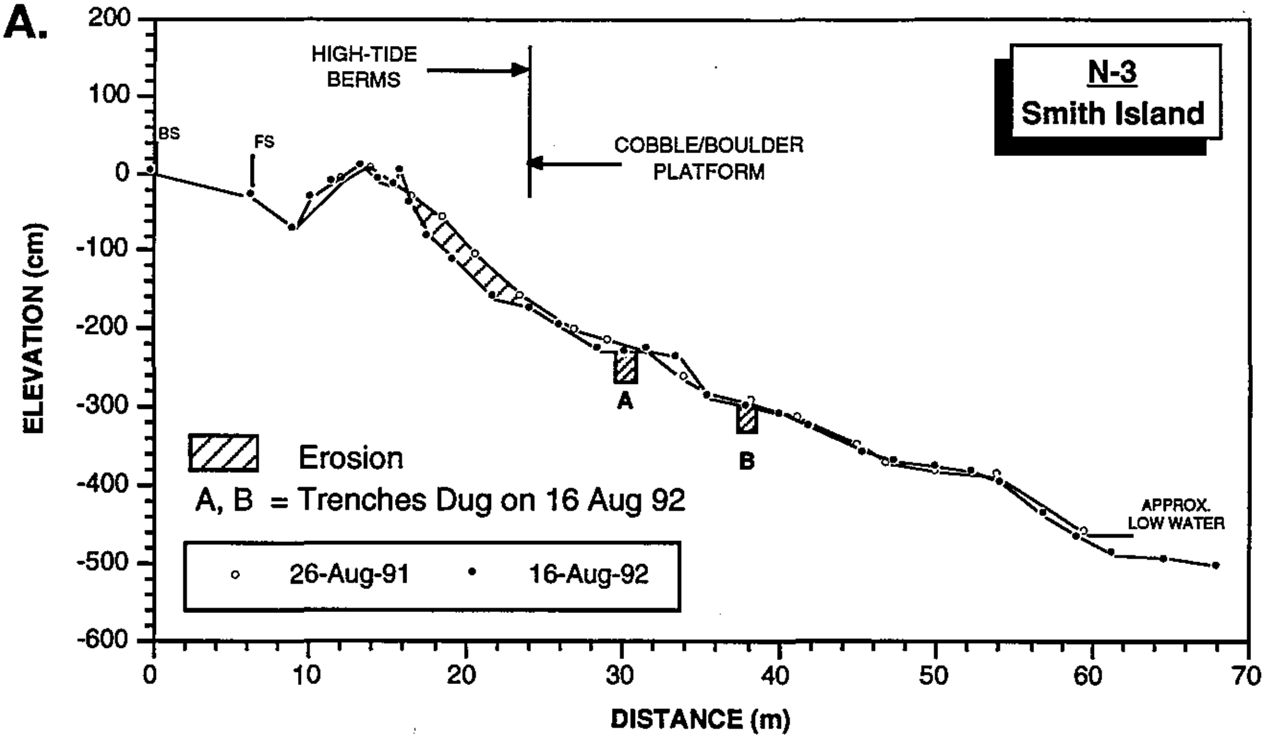
The storm season of 1991/1992 did not bring about as much change as the previous storm season. In August 1992, subsurface oil in the upper platform remained at about the same depths or shallower, but it was described as MOR. TPH concentrations for the two samples collected were 8,150 and 12,420 mg/kg (Table 2-2). Figure 3-12 shows photographs of trench B (see Figure 3-10 for trench B location and description). A high water table prevented determination of the total oiled interval. Figure 3-12B shows the degree of oiling of sediments from the base of the trench (below the water table). The long-term persistence of large amounts of subsurface oil at this site is a function of the deep penetration into the permeable sediments and the well-established armor which slows reworking. The subsurface oil has weathered slowly, and it remains fluid enough to generate sheens even during calm weather. Sheens were observed during our visit in August 1992, emanating from the middle beachface and evident as iridescent films on the surface sediment. It is likely that tidal flushing will continue to be an important mechanism for the removal of subsurface oil from this site until the oil weathers to the point of becoming too viscous to release sheens. However, the relatively low angle of the slope of the rock platform (4.3°) probably partially explains why flushing has been slower at this station than at those with steeper slopes (e.g., N-17 on Perry Island and N-4 on Smith Island, which have upper platforms that slope seaward at 6°).

Figure 3-10. (Facing Page) Station N-3 at Smith Island.

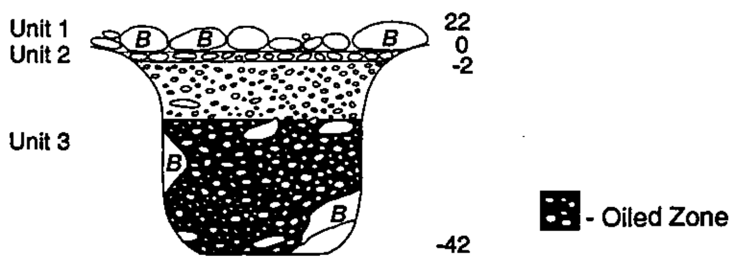
A. Beach profiles measured on 26 August 1991 and 16 August 1992. Note erosion of high-tide berms.

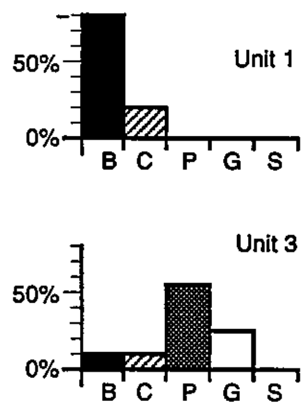
B. Description of trenches A and B (located on diagram A), showing presence of subsurface oil under conspicuous surface armor.

A.



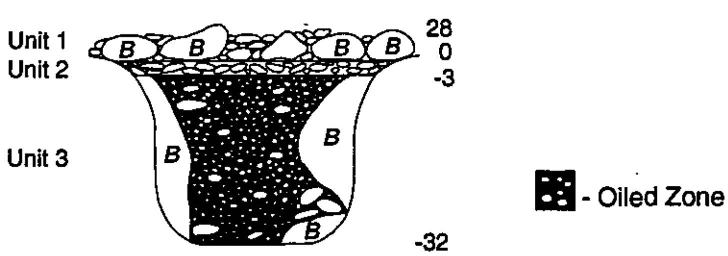
B. **TRENCH A**

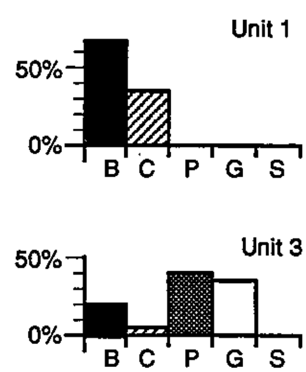




Unit 1: Boulder armor; 22 cm thick.
Unit 2: No oil; layer of cobbles beneath surface armor; 2 cm thick.
Unit 3: Moderately oiled (MOR) 14-42+ cm (did not reach the bottom of the oil layer); chemical sample (35-42 cm).

TRENCH B





Unit 1: Boulder armor; 28 cm thick.
Unit 2: No oil; layer of cobbles beneath surface armor; 3 cm thick.
Unit 3: Moderately oiled (MOR) 3-37+ cm (did not reach the bottom of the oil layer); Black oil droplets on water table; chemical sample (15-25 cm).

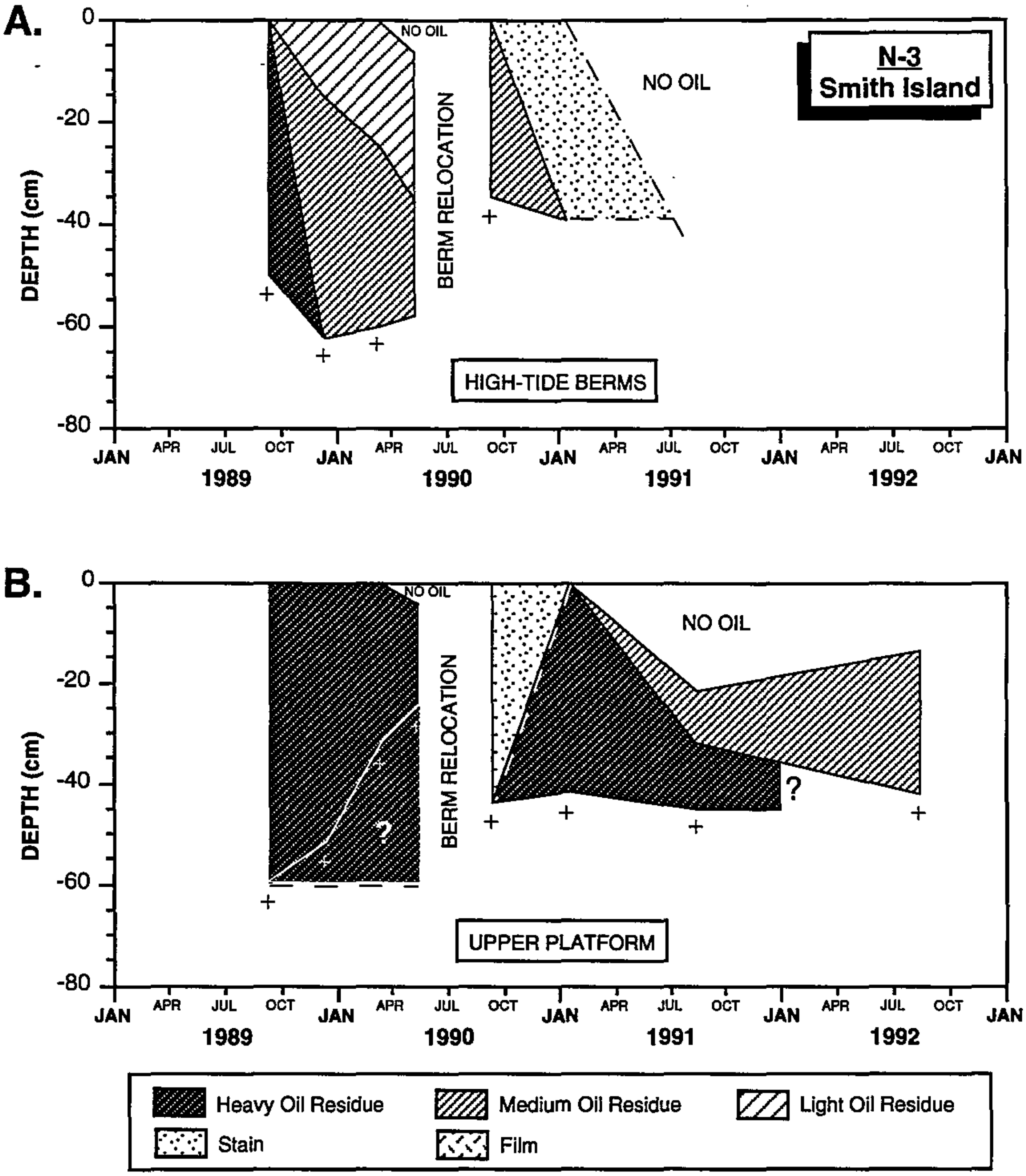


Figure 3-11. Time-series plot of the interval and degree of subsurface oil at station N-3 (Smith Island), based on trench descriptions and chemical analyses, for the (A) high-tide berms and (B) upper platform.

Table 3-3. Historical summary of the interval and degree of subsurface oil at station N-3 (Smith Island). Depths are reported in centimeters.

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

Station N-7 (Knight Island)

Introduction. This station, which was surveyed for the tenth time in August 1992, is located on an east-west oriented pocket beach on the north side of the major headland to the north of the entrance to the Bay of Isles (Figure 1-1). The fetch perpendicular to the beach is only five km, but open effective fetches of 15 to 20 km to the northeast (40° to beach) and 60 km to the east-northeast (60° to beach) allow for significant wave activity during major storms. Like the other stations in the cobble/boulder platform with berms class, this site contains an uplifted shore platform infrastructure, as a result of the 1.2 m uplift during the 1964 earthquake.

This beach was one of the 1990 sites selected for monitoring the effectiveness of bioremediation on subsurface oil. Our profile line was on the boundary between the area fertilized with Customblen and the part not fertilized at all. At the end of the test on 8 September 1990, the entire beach was treated on an experimental basis with Inipol.

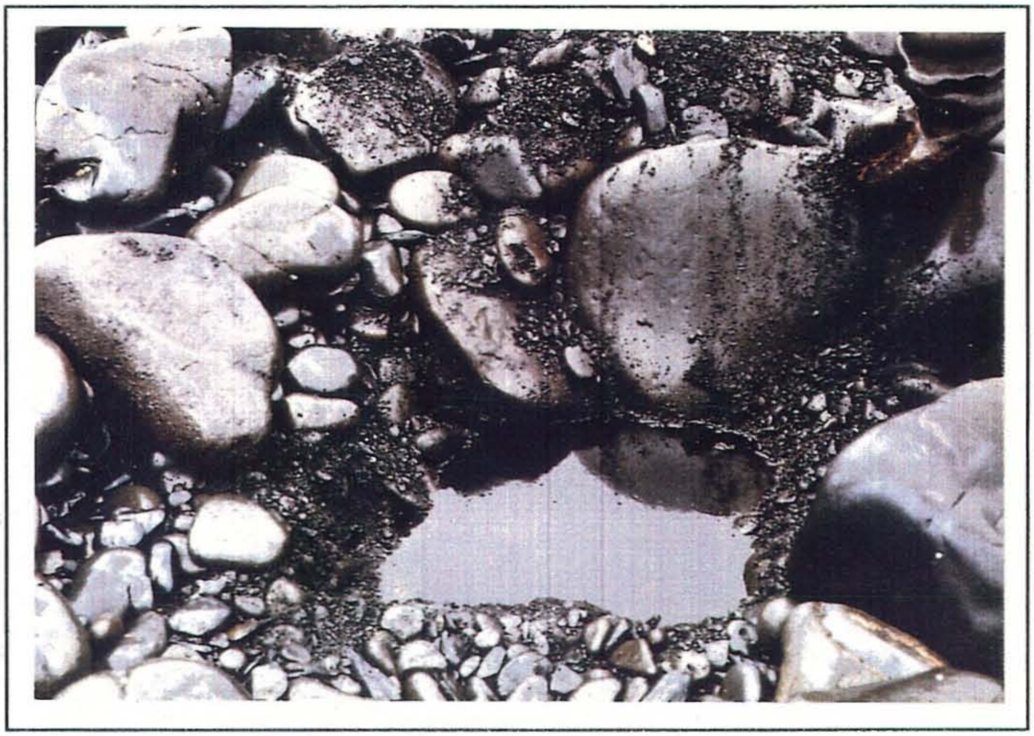
Morphology and sediments. As shown in Figure 3-13, this beach has a high storm berm with minor berms on its shoreward face and a broad cobble/boulder platform. The high-tide berms at this station, which are composed of pebbles and cobbles, have showed considerable activity throughout the study. As the comparative profiles in Figure 3-13B show, a new spring berm formed in the interval between the August 1991 and August 1992 surveys. On the other hand, the other parts of the profile, the storm berm and the cobble/boulder platform, have showed no change throughout the study. Berm-like ridges are notably absent from the cobble/boulder platform except in a very subtle form.

Figure 3-12. (Facing Page) Photographs of trench B at station N-3 (Smith Island) on 16 August 1992.

A. The water table is at a depth of 28 cm. Note the black oil layer on the standing water surface, and oil sheens on the clasts. Medium oil residue (MOR) was observed from 3-32+ cm. A sample from the interval 15 to 25 cm contained 12,420 mg/kg TPH.

B. Close-up of sediments removed from trench B. The oiling was characterized as MOR (medium oil residue).

A.



B.

The sediments on this beach, described in detail by Michel and Hayes (1991), show a marked coarsening in an offshore direction, are relatively poorly sorted, and contain some subangular clasts. Boulders make up 40 to 50 percent of the surface sediments of the lower platform. Armoring is well developed all along the upper and lower platforms (as shown in trench descriptions; Figure 3-14), which slope offshore at angles of 5° and 3° respectively, relatively low angles for the raised shore platforms of Prince William Sound.

All of the above criteria suggest that this beach is not as frequently reworked by storm waves as the beaches at stations N-1, N-3, and N-17. Nevertheless, the presence of the large storm berm and the abraded coarse gravel present indicate that the entire beach is occasionally reworked during infrequent, very large storms.

Berm relocation. No berm relocation was conducted on this beach, but, interestingly, the subsurface oil in the high-tide berm area was cleaned by natural processes (discussed below).

Surface oil. In September 1989 the upper third of the beach was 45 to 100 percent covered by oil. By May 1990, however, only five percent surface oil coverage remained. No surface oil was observed along the profile during the August 1991 and August 1992 surveys (Table 3-1).

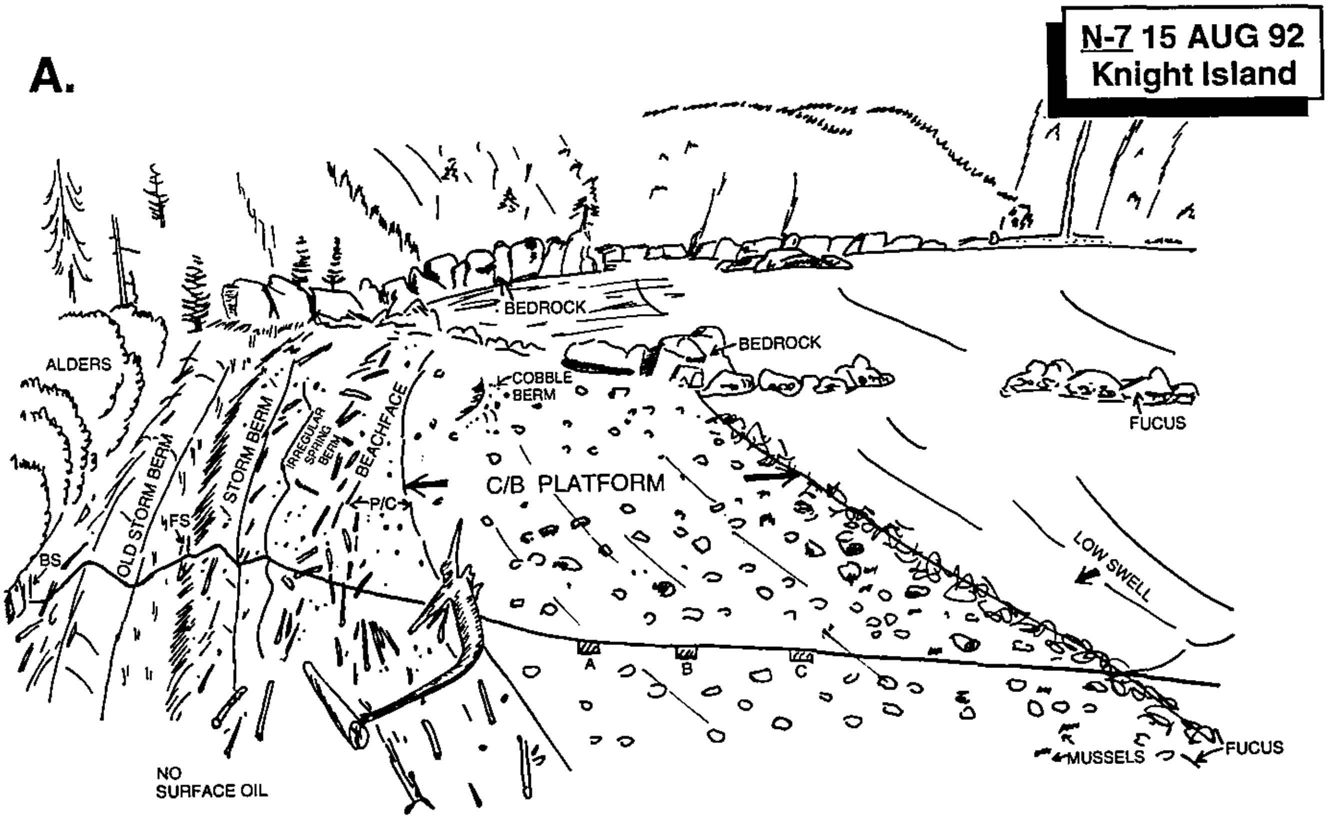
Subsurface oil. A summary of the interval and degree of subsurface oil at N-7 for the period of September 1989 through August 1992 is shown in Table 3-4 and plotted in Figure 3-15. The mobility of the sediments of the high-tide berms is reflected in the frequent changes in depth and degree of oiling over the first winter, and the complete natural removal of oil after the second winter.

Figure 3-13. (Facing Page) Station N-7 (Knight Island).

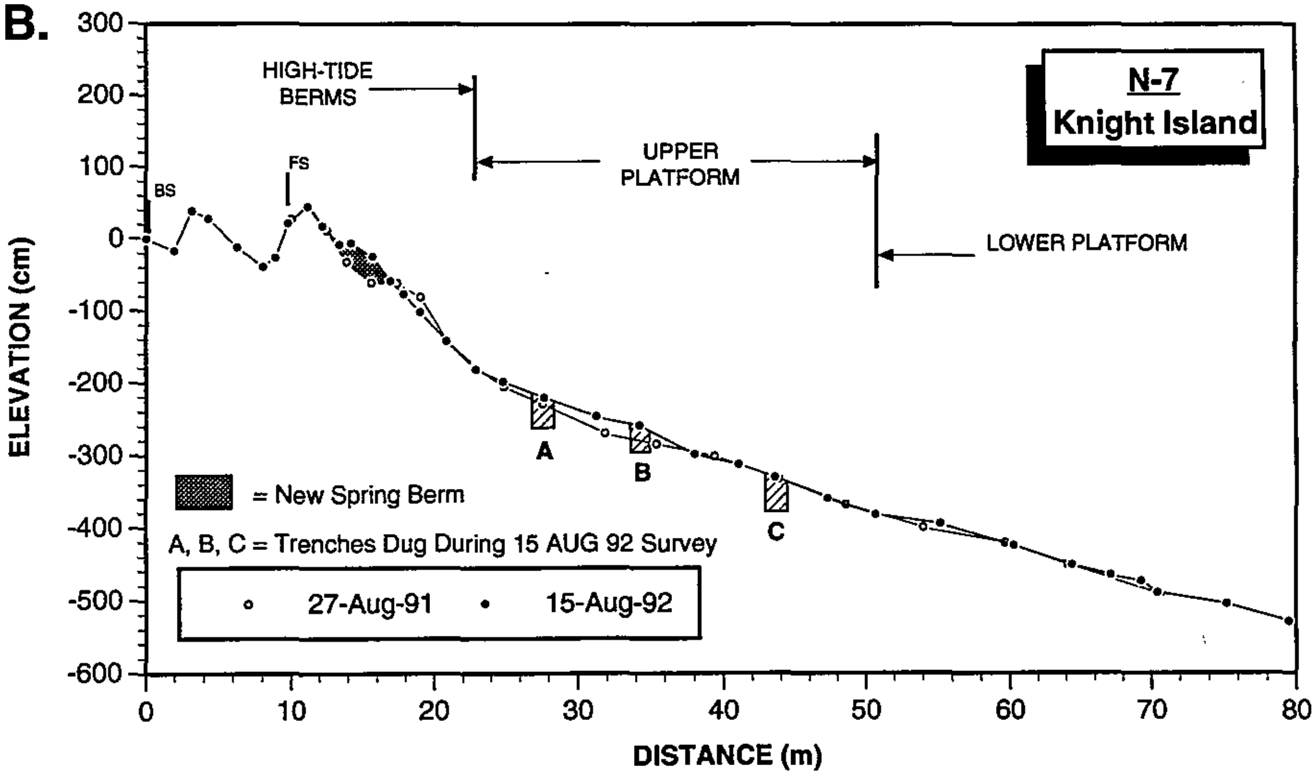
A. Field sketch on 15 August 1992.

B. Comparative beach profiles for surveys conducted 27 August 1991 and 15 August 1992. Note development of new spring berm and relative stability of the rest of the profile.

A.


N-7 15 AUG 92
Knight Island
ALDERS
BEDROCK
BEDROCK
COBBLE BERM
OLD STORM BERM
STORM BERM
IRREGULAR SPRING BERM
BEACHFACE
C/B PLATFORM
P/C
FS
BS
FUCUS
LOW SWELL
A
B
C
MUSSELS
FUCUS
NO SURFACE OIL

B.


N-7
Knight Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
BS
FS
A
B
C
= New Spring Berm
A, B, C = Trenches Dug During 15 AUG 92 Survey
27-Aug-91
15-Aug-92
ELEVATION (cm)
DISTANCE (m)
300
200
100
0
-100
-200
-300
-400
-500
-600
0
10
20
30
40
50
60
70
80

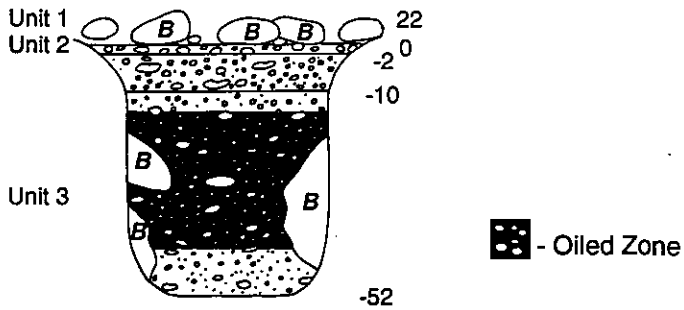
A detailed discussion of the subsurface oil pattern at the high-tide berm zone is warranted to better explain the plots (Figure 3-15A). In September 1989 heavy oil (6,600 mg/kg) extended from the surface to more than 20 cm in the pebble berm. Over the winter, these berms were being reworked, and the oil content down to 50 cm was reduced to moderate in December, and light in January. However, it is obvious that these berms had been eroded by the time of the February 1990 survey, because about 40 cm of lightly oiled sediment had been removed and a deep layer of heavily oiled sediments (containing 5,100 mg/kg of oil) was closer to the surface (10-40 cm). Furthermore, by May 1990 nearly all of the subsurface oil in this zone had been removed and only oil-stained pebbles were observed. The amount of oil stain decreased consistently until January 1991, after which the sediments were visually free of oil. Thus, on a relatively exposed beach, with a series of mobile, pebble berms, the subsurface oil was reduced to stain after one storm season. It took two storm seasons to remove all traces of subsurface oil.

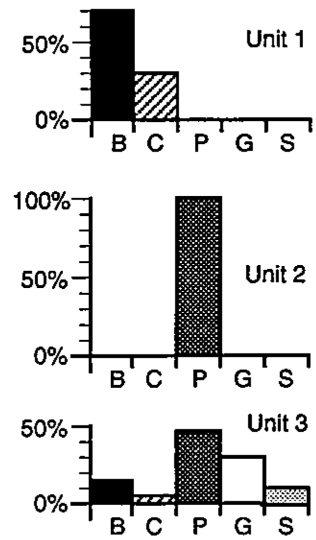
The persistence of subsurface oil in the upper platform (Figure 3-15B) at N-7 was completely different than in the pebble berms. The subsurface oil was characterized as heavy (averaging around 10,000 mg/kg) through January 1991. The large and stable armor of cobbles and boulders slowed natural removal processes, in spite of heavy application of Customblen fertilizer during 1990 as part of the effectiveness monitoring study conducted at this beach. Also, similar to station N-3 on Smith Island, the heavily oiled subsurface sediments extended to the lower platform (Table 3-4), and persisted until the January 1991 survey. Figure 3-15B shows the persistence of heavy oil in the upper platform to depths of at least 75 cm, with heavy oil right to the surface through January 1991. The platform is very stable and the beach profiles show almost no change in the surface elevation of the platform (Michel and Hayes, 1991; Figure 8). During the August 1991 survey, for the first time, the top 15 to 30 cm of sediments on the upper platform appeared unoiled. However, below this depth, the sediments remained heavily oiled; samples from these trenches in this zone averaged 7,500 mg/kg oil, about

Figure 3-14. (Facing Page) Trench descriptions for station N-7 (Knight Island) on 15 August 1992. See Figure 3-13B for location of the trenches along the profile. All three trenches are located on the upper platform. Note that the top ±15 cm are free of oil in this zone.

N-7 KNIGHT ISLAND, 13 AUGUST 1992

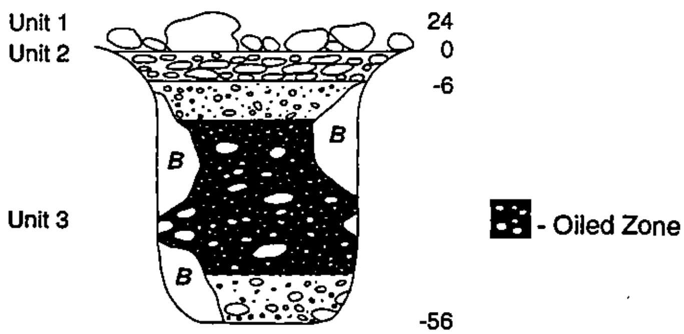
TRENCH A

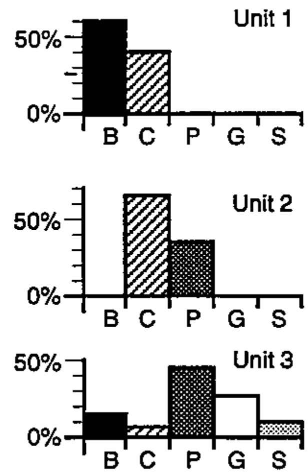




Unit 1: Boulder armor; 22 cm thick.
Unit 2: No oil; layer of pebbles beneath surface armor; 2 cm thick.
Unit 3: (MOR) 14-42 cm; clean beneath; unit becoming sandier near the bottom of the trench; chemical sample (25-40 cm).

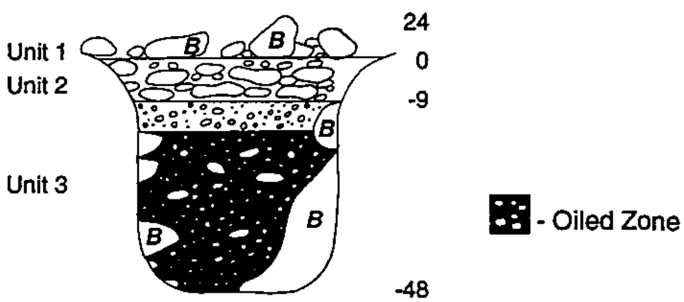
TRENCH B

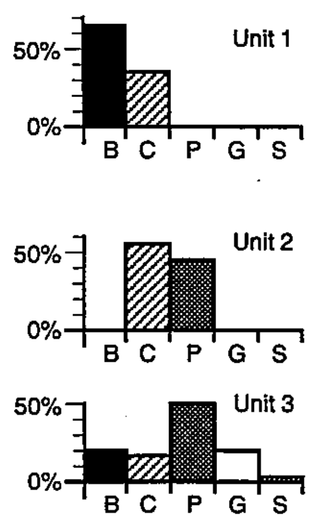




Unit 1: Boulder armor; 24 cm thick.
Unit 2: No oil; layer of cobbles/pebbles beneath surface armor; 6 cm thick.
Unit 3: (MOR) 14-46; clean beneath; unit becoming sandier near the bottom of the trench; chemical sample (35-45 cm).

TRENCH C





Unit 1: Boulder armor; 24 cm thick.
Unit 2: No oil; layer of cobbles/pebbles beneath surface armor; 9 cm thick.
Unit 3: (MOR) 14-48 cm (did not reach the bottom of the oil layer); unit becoming sandier near the bottom of the trench; chemical sample (35-45 cm).

Table 3-4. Historical summary of the interval and degree of subsurface oil at station N-7 (Knight Island). Depths are reported in centimeters.

Survey Date	High-tide Berms	Upper Platform	Lower Platform
Sept. 1989	0-20+ (HOR)	0-22+ (HOR)	
Dec. 1989	0-30 (MOR) 30-50 (LOR)	0-38+ (HOR)	0-16+ (HOR)
Jan. 1990	0-50+ (LOR)	0-48+ (HOR)	5-15 (HOR) 15-45 (LOR)
Feb. 1990	0-10 (LOR) 10-40 (HOR) 40-50 (LOR)	0-58 (HOR) 58-62+ (LOR)	5-45 (HOR) 45-52+ (MOR)
May 1990	0-36+ (ST)		10-20 (MOR)
Sept. 1990	20-38 (ST)	0-36+ (HOR)	
Jan. 1991	0-20 (ST)	0-35 (HOR)	No oil
Aug. 1991	No oil	30-56+ (HOR)/15-75+ (HOR)	
Aug. 1992		14-42 (MOR)/16-48+ (MOR)	

25 percent lower than previous periods. During the August 1992 survey, all the trenches showed ±15 cm of clean sediments overlying deeper sediments characterized as MOR (Figure 3-14). The TPH content of samples of MOR sediments from trenches A, B, and C ranged between 14,700 and 18,710 mg/kg. (Table 2-2). These TPH levels were the highest measured of the 16 samples collected during the August 1992 survey, but they are, surprisingly, among the most weathered. The other stations were also treated with both types of fertilizers, so the reason for the extensive weathering is not known.

It is interesting to note that clean sediments were encountered in trenches A and B at depths of 42 and 46 cm below the surface, but not in trench C, although the water table prevented digging the trench below 48 cm. The deepest penetration has always been in the lower part of this zone, near trench C on Figure 3-13A. The stable armor has continued to slow removal of subsurface oil from this beach, even 3.5 years after the spill.

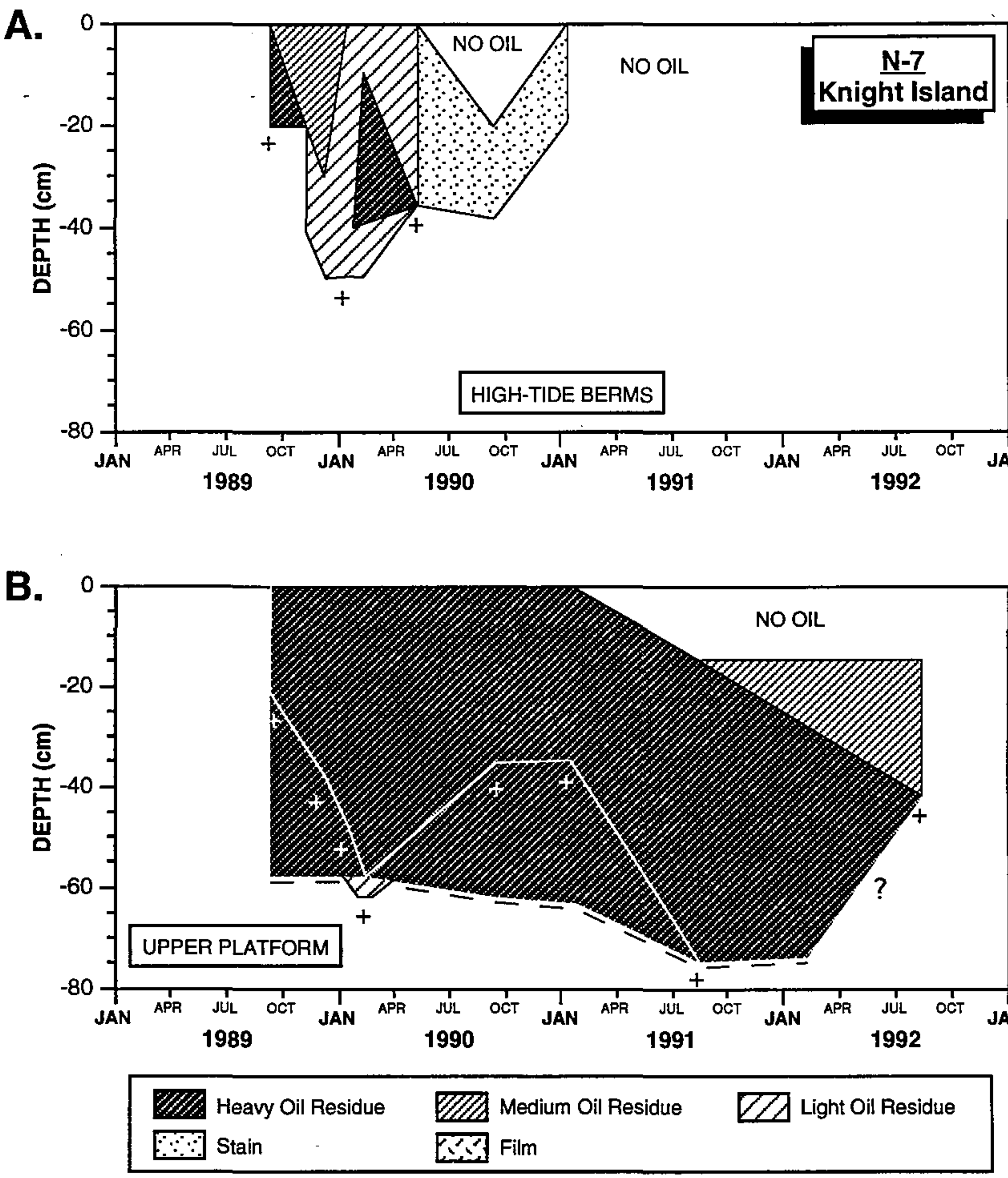


Figure 3-15. Time-series plot of the interval and degree of subsurface oil at station N-7 (Knight Island), based on trench descriptions and chemical analyses, for (A) high-tide berms and (B) upper platform. Note the near-complete removal of subsurface oil from the berms after the first storm season, and the persistence of oil in the upper platform through August 1992.

In summary, the following excerpt from the 1991 report (Michel and Hayes, 1991) still applies: "Based on all these results, the subsurface sediments at N-7 are likely to remain oiled for an extended period. This station represents one of the worst-case end members for raised cobble/boulder platforms with berms, and it may be representative of gravel beaches located on intermittently exposed shorelines, such as along Puget Sound. The oiled sediments below the stable surface armor are not effectively flushed by tidal pumping because of the lower porosity of the finer sediments and the low angle of the platform slope. Mobilization of the surface armor will be infrequent."

Station N-15 (Latouche Island)

Introduction. This station is located near the center of a northwest-southeast oriented pocket beach on the northeast corner of Latouche Island. The fetch distance perpendicular to the beach is only 25 km, but there is an effective fetch of 40 km in the north-northeast direction (70° angle with beach). Therefore, this beach is subject to considerable wave action. This area was uplifted 3.5 m during the 1964 earthquake, the most of any of the study sites. The gravel of the cobble/boulder platform are underlain by a reddish, fine-grained sediment. This beach has been surveyed 12 times.

Morphology and sediments. The morphology and sediments of this beach have been affected significantly by a major berm-relocation project carried out in early September 1990 (discussed below). The nature of the beach in August 1992 is illustrated by the topographic profile and surface sediment distribution plot in Figure 3-16, and by the field sketch in Figure 3-17. At the time of the survey, a relatively wide zone of high-tide berms had evolved, and three prominent berm-like ridges were present on the upper and lower platforms. As shown in Figure 3-16B, the surface sediment distribution pattern closely mimics the beach topography, with: 1) pebbles and cobbles predominately on the high-tide berms; 2) grain size increasing measurably in an offshore direction to more than 50 percent boulders near low water; and 3) the seaward faces of the berm-like ridges containing notably more boulders than the intervening swales.

The sediments of this pocket beach at N-15 have been studied in considerable detail, and the results are given in Michel and Hayes (1991). The clasts are very well rounded and well sorted, and the upper and lower platforms are perfectly armored (see photograph in Figure 3-18A). Longshore sediment transport is clearly northwest to southeast, as evidenced by the facts that: 1) there is a general decrease in grain size in that direction; 2)

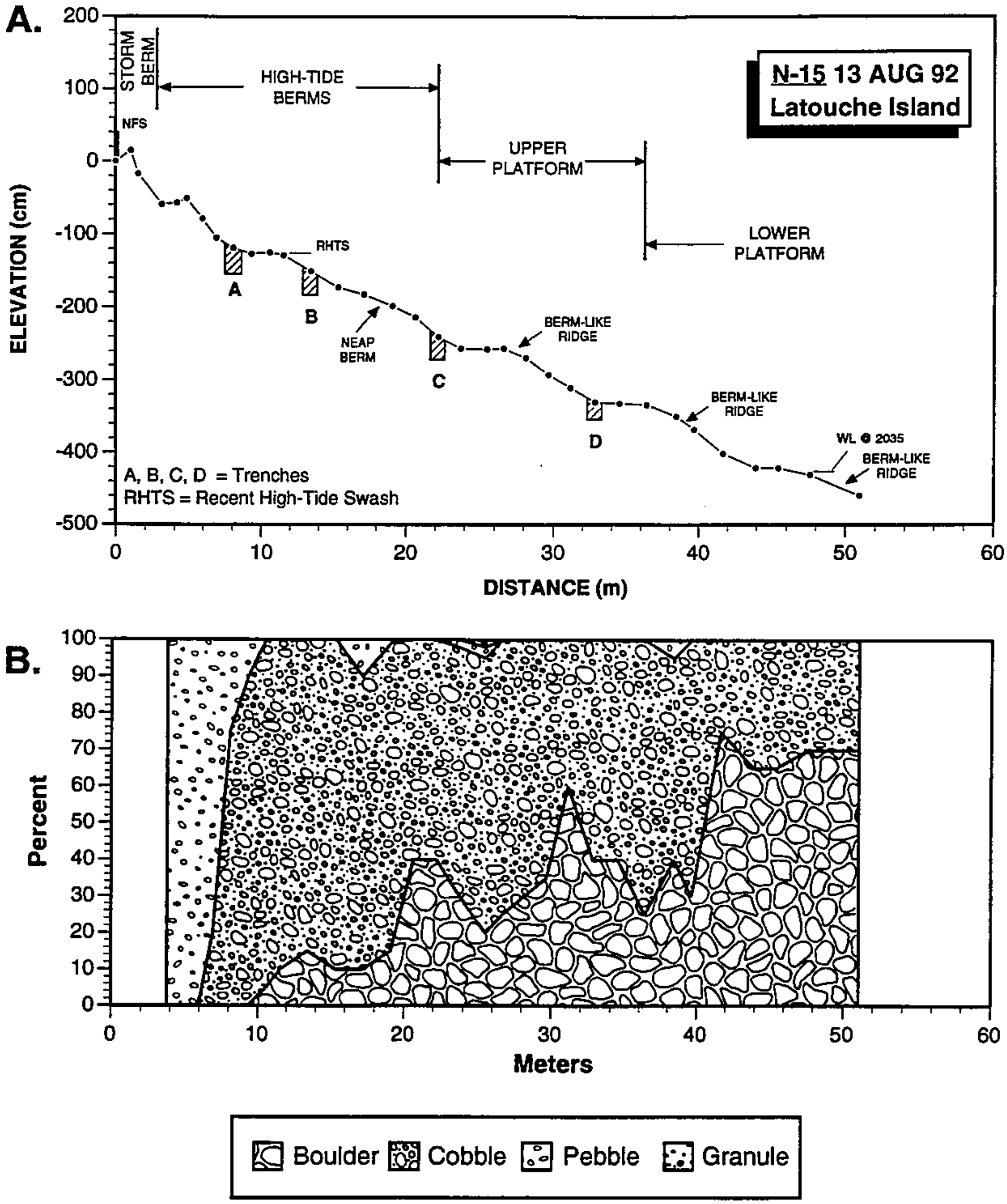


Figure 3-16. Station N-15 (Latouche Island).

A. Beach profile on 13 August 1992.

B. Surface sediment distribution along profile on 13 August 1992. Note increase in grain size in offshore direction and abrupt increase in grain size on the seaward face of the berm-like ridges.

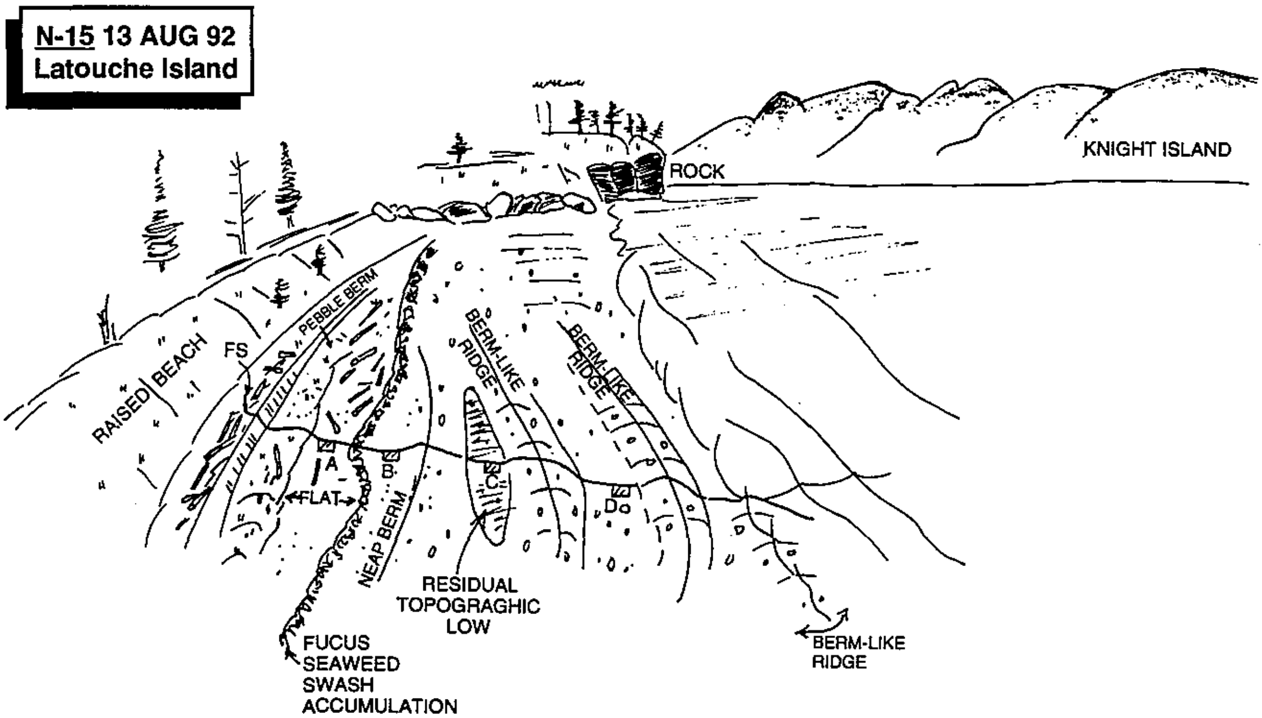


Figure 3-17. Field sketch of station N-15 (Latouche Island) on 13 August 1992. Note prominent berm-like ridges and residual topographic low resulting from September 1990 berm-relocation project.

the berm-like ridges are oriented obliquely to the beach, indicating transport to the southeast; 3) sediment clasts become better rounded in that direction; and 4) other indicators, such as minor natural groins (e.g., sediment accumulation updrift of large logs).

Berm relocation. The berm relocation at this site was the second largest of the projects we studied, after the one at Point Helen. The project was described as follows in Michel and Hayes (1991; p. 122):

"In 1990, no work was conducted on this site until early September; during our visit on 5 September, crews were conducting a "berm relocation." Our profile was run right through the area of active excavation, which extended down to the red oxidized zone. Excavated sediments had been piled on top of the upper platform, covering a zone about 25 m wide. After tidal flushing of the exposed sediments, they were pushed back into the original position and Inipol/Customblen were applied. This "berm relocation" actually consisted of tilling of the middle part of the beach, wholesale excavation of the entire upper beach, placement of this material throughout the middle intertidal zone for tilling and tidal flushing, and then replacement. A small tracked bobcat was used for all transport of sediment and filling of the excavated sediment. Between each high tide, the bobcat would "till" the pile of sediments, attempting to turn over the pile and expose more oiled sediments to the surface. This type of berm relocation is disruptive of the upper and parts of the middle intertidal zone. However, the station is very exposed to the predominant storm waves, so the sediments may be reworked into their original distribution over the storm season. Evaluating the sediment and biological recovery will be part of ongoing surveys. Exxon reviewers of this report state that "the berm relocation program was designed to avoid relocation of oiled material or sediments to the lower intertidal areas and other sections of the intertidal zone which were either armored or had abundant biota. In most cases, the design was carried out well and no other problems were encountered" (John Wilkenson; letter dated 25 January 1991)."

The actual recovery of this beach following the berm-relocation project has been surprisingly slow. Figure 3-19 shows all the surveys carried out between 26 May 1990, before the berm relocation, and 13 August 1992. The plot in Figure 3-19B, which compares the 5 September 1990 survey (conducted during the relocation process) with the 22 January 1991 survey, shows that the excavation pile left on the upper and lower platforms was not returned to the excavated pit by wave action during the storm season of 1990-91. We believe that the sediments in the pile were transported to the southeast by the strong longshore currents existing on this beach. As pointed out earlier (Michel and Hayes, 1992), this profile changed very little between the January 1991 and August 1991 surveys (see Figure 3-19C). The original excavation pit was still not completely filled-in by the time of the 13 August 1992 survey (see Figures 3-17 and 3-19D). However, some berm material had been re-deposited on the upper profile. In fact, the zone of high-tide berms had expanded significantly in an offshore direction. Inspection of surface sediment distribution patterns for surveys since the berm relocation reveals that the surface sediments have not returned to their May 1990 configuration. Pebbles and cobbles extend further seaward several meters in response to the expansion of the zone of high-tide berms. As shown by the trench descriptions in Figure 3-20, however, surface armoring was beginning to recover on the upper platform (trench C) by August 1992.

In summary, the beach at station N-15 has not completely recovered to either the morphological or sedimentological configuration it had before the berm-relocation project was carried out. Two factors, the large scale of the operation and the strong longshore transport in the area, are thought to contribute most to this slow recovery.

Surface oil. During the September 1989 survey, much of the upper intertidal zone had a 100 percent surface cover of heavy oil. By May 1990, the surface oil had been reduced a maximum of 10 to 15 percent stain. However, as a result of the berm-relocation project, as much as 60 percent oiling was observed in the old excavation area during the August 1991 survey (Table 3-1). The surface sediments along the profile were essentially clean during the August 1992 survey.

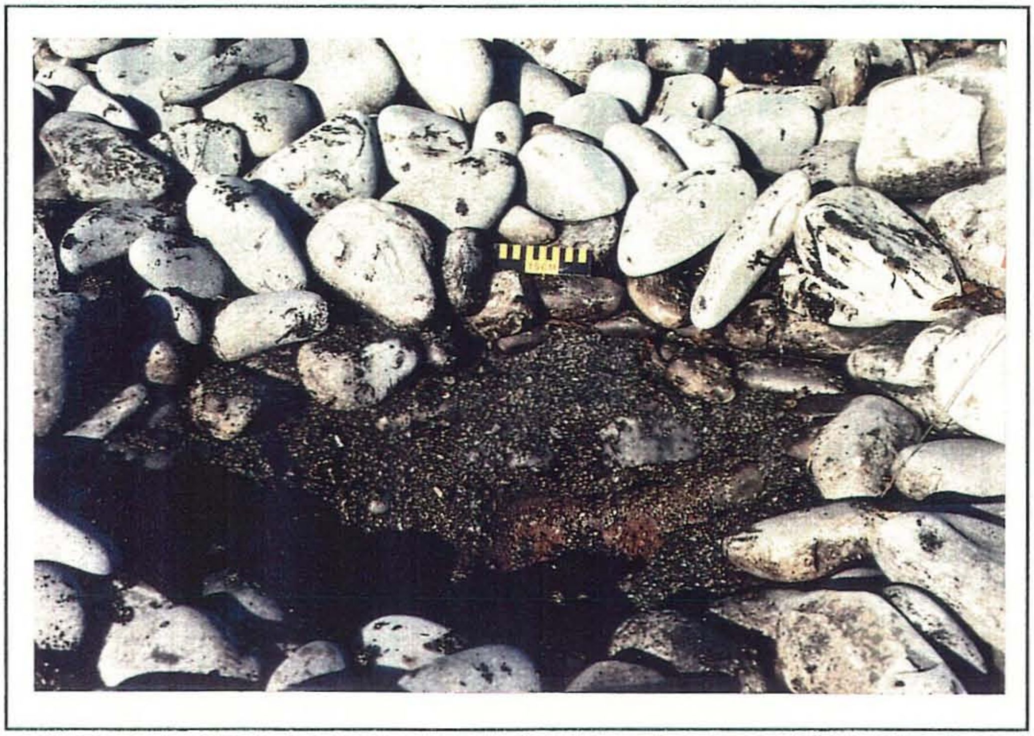
Subsurface oil. The measurements of subsurface oil intervals and degree of contamination at station N-15 are summarized in Table 3-5, and the data for the upper platform are plotted in Figure 3-21. Oiling on the cobble armor in the upper platform, which was 20 to 30 cm thick, was characterized as cover (CV), coat (CT), or stain (ST). Figure 3-21 shows the steady removal of oil from these cobbles over the winter of 1989-90, with the top half being clean as of May 1990 (Figure 3-18A). However, the cobble armor overlaid a tightly packed mixture of mostly pebbles with cobbles and granules, which were very heavily oiled, containing 10,000 to 42,000 mg/kg oil. There was no change in the degree of oiling in this oiled layer up until the berm relocation—it ended sharply at an impermeable oxidized layer at a depth of 40 to 45 cm, shown in Figure 3-18A. In fact, this impermeable layer was the prime reason for the very high oil content in the overlying sediments.

Figure 3-18. (Facing Page) Photographs of trenches at station N-15 (Latouche Island).

A. Trench C on 26 May 1990 showing the well-developed cobble armor overlying a heavily oiled layer, which in turn overlies an impermeable, red oxidized layer.

B. Trench C on 13 August 1992. See Figure 3-16 for location. The subsurface sediments on the platform remain moderately oiled. Compare with trench description in Figure 3-20.

A.



B.

As a result of the major tilling/excavation activities during September 1990, the oil content of the sediments was greatly reduced. The sediments (mostly pebbles) slowly being re-formed into spring-tide berms were free of oil by August 1992 (Figure 3-20 and Table 3-5), though the year earlier they contained 3,200 mg/kg oil. Note that trenches A and B had no subsurface oil (Figure 3-20). However, trench C, shown in Figure 3-18B, had moderately oiled sediments at 10 to 20+ cm, with a sample from 10 to 15 cm containing 6,640 mg/kg TPH below a clean surface layer of cobbles and 10 cm of pebbles with an oily film. It appears that some of the oiled sediment is accumulating below the cobble armor as it re-forms, in spite of the extensive tilling and excavation two years ago.

The resilience of subsurface oil in this exposed cobble platform is phenomenal. Without the intensive cleanup carried out at this site, the original layer of heavily oiled fine gravel would have surely formed an asphalt pavement below the cobble armor. The impermeable layer must limit the degree of tidal flushing. However, it is surprising that the thin layer of sediments (less than 60 cm) is not reworked to greater depths on the platform, even as the pile of excavated and tilled sediments is redistributed. These results support the recommendation that berm-relocation projects be considered on a site-specific basis.

Figure 3-19. (Facing Page) Repetitive beach surveys at station N-15 (Latouche Island).

A. 26 May 1990 vs. 5 September 1990, which shows the effect of the large berm-relocation project of early September 1990.

B. 5 September 1990 vs. 22 January 1991, which shows loss of sediment from the profile.

C. 22 January 1991 vs. 28 August 1991, which shows little change.

D. 28 August 1991 vs. 13 August 1992, which shows some new berm development in the old excavation area.

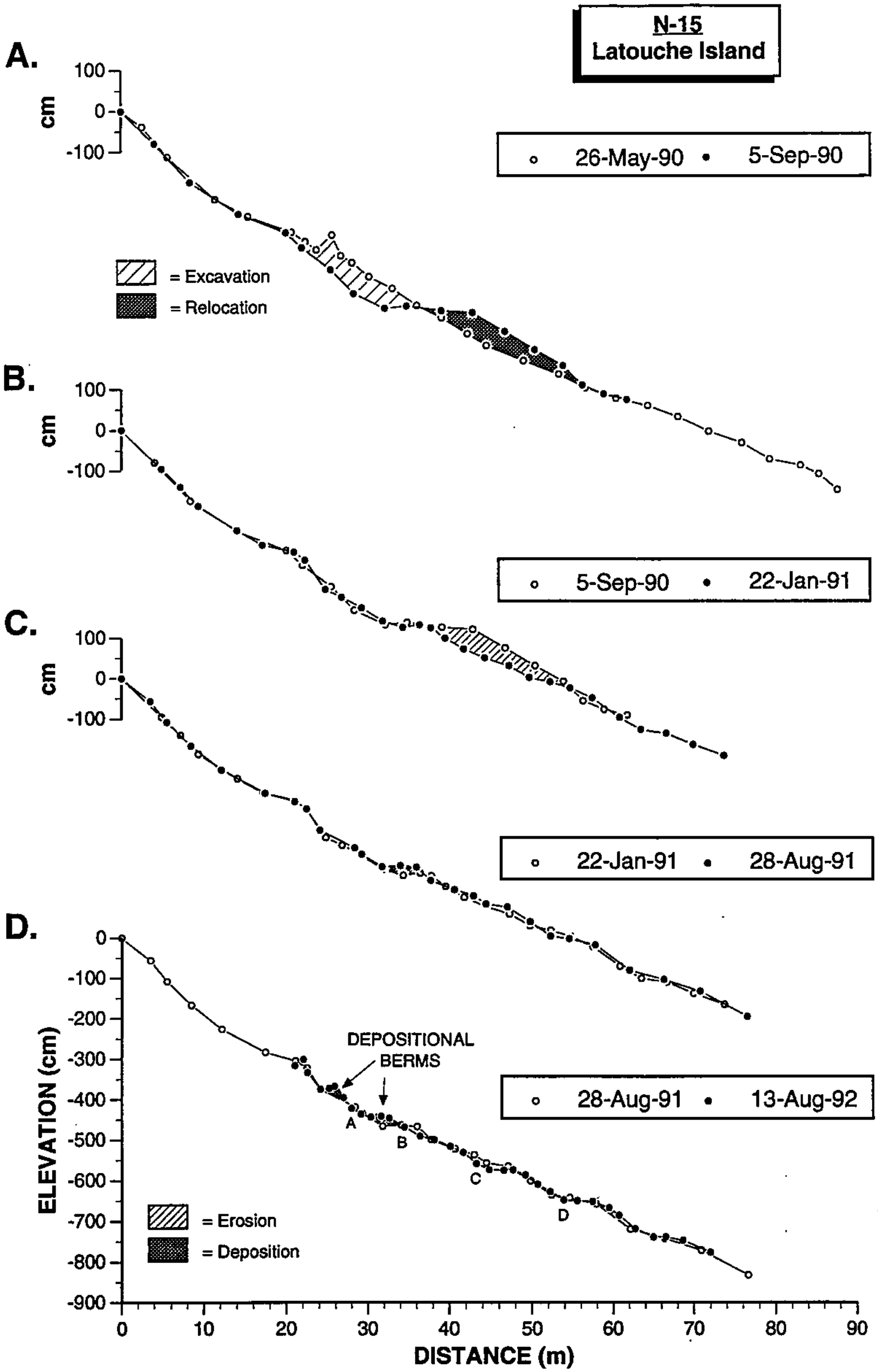

N-15
Latouche Island
A.
B.
C.
D.
cm
100
0
-100
26-May-90
5-Sep-90
= Excavation
= Relocation
5-Sep-90
22-Jan-91
22-Jan-91
28-Aug-91
28-Aug-91
13-Aug-92
DEPOSITIONAL
BERMS
A
B
C
D
= Erosion
= Deposition
ELEVATION (cm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
DISTANCE (m)
0
10
20
30
40
50
60
70
80
90

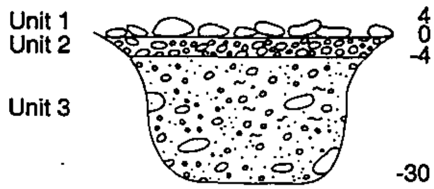
Table 3-5. Historical summary of the interval and degree of subsurface oil at station N-15 (Latouche Island). Depths are reported in centimeters.

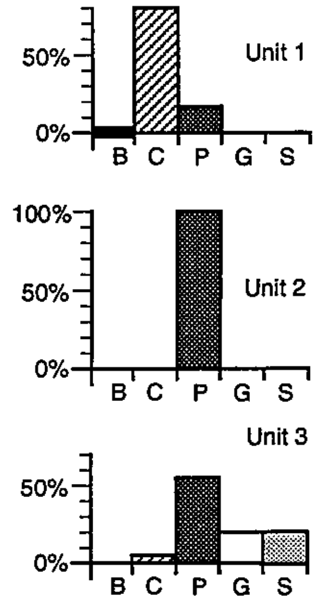
Survey Date	High-tide Berms	Upper Platform	Lower Platform
Sept. 1989	0-22 (CV) 22-42 (HOR)	0-20 (CV) 20-42 (HOR)	0-10 (MOR)
Oct. 1989		0-20 (CT) 20-44+ (HOR)	
Nov. 1989	0-30 (ST) 30-48 (MOR)	0-20 (ST) 20-40+ (HOR)	0-16 (OF)
Dec. 1989	0-30+ (ST)	0-20 (ST) 20-28+ (HOR)	0-23 (LOR)
Jan. 1990		0-20 (ST) 20-34+ (HOR)	
Feb. 1990		0-20 (ST) 20-41 (HOR)	
May 1990		15-26 (ST) 26-40 (HOR)	
Major tilling and berm relocation—September 1990			
Jan. 1991	0-25 (ST)	0-20 (ST) 20-46+ (LOR)	
Aug. 1991	0-15 (ST) 15-60 (LOR)	0-15 (ST) 15-60 (LOR) 50-60+ (MOR)	No oil
Aug. 1992	No oil	0-10 (OF) 10-20+ (MOR)	

Figure 3-20. (Facing Page) Trench descriptions for station N-15 on 13 August 1992. See Figure 3-16 for location of trenches. Note that the armor is beginning to reform. Oiled sediments were found only in trench C.

N-15 LATOUCHE ISLAND, 13 AUGUST 1992

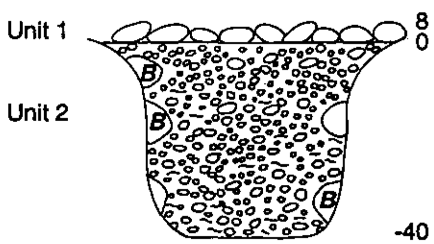
TRENCH A

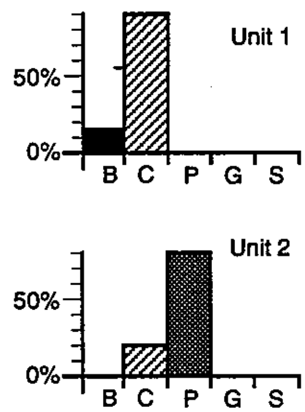




Unit 1: Surface layer of cobbles; 4 cm thick.
Unit 2: No oil; layer of pebbles; 4 cm thick.
Unit 3: No oil; C/P/G/S with organic detritus.

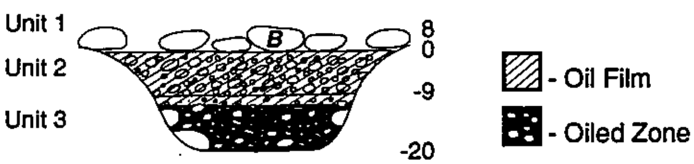
TRENCH B

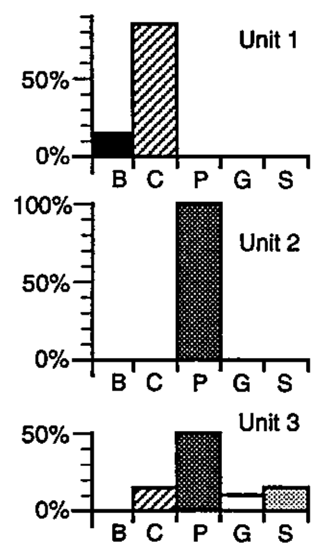




Unit 1: Boulder/cobble armor; 8 cm thick.
Unit 2: No oil; cobbles/pebbles with organic detritus.

TRENCH C





Unit 1: Boulder/cobble armor; 8 cm thick.
Unit 2: (VLOR) film 0-10 cm; layer of pebbles beneath surface armor.
Unit 3: (MOR) 10-20+ cm (did not reach the bottom of the oil layer).

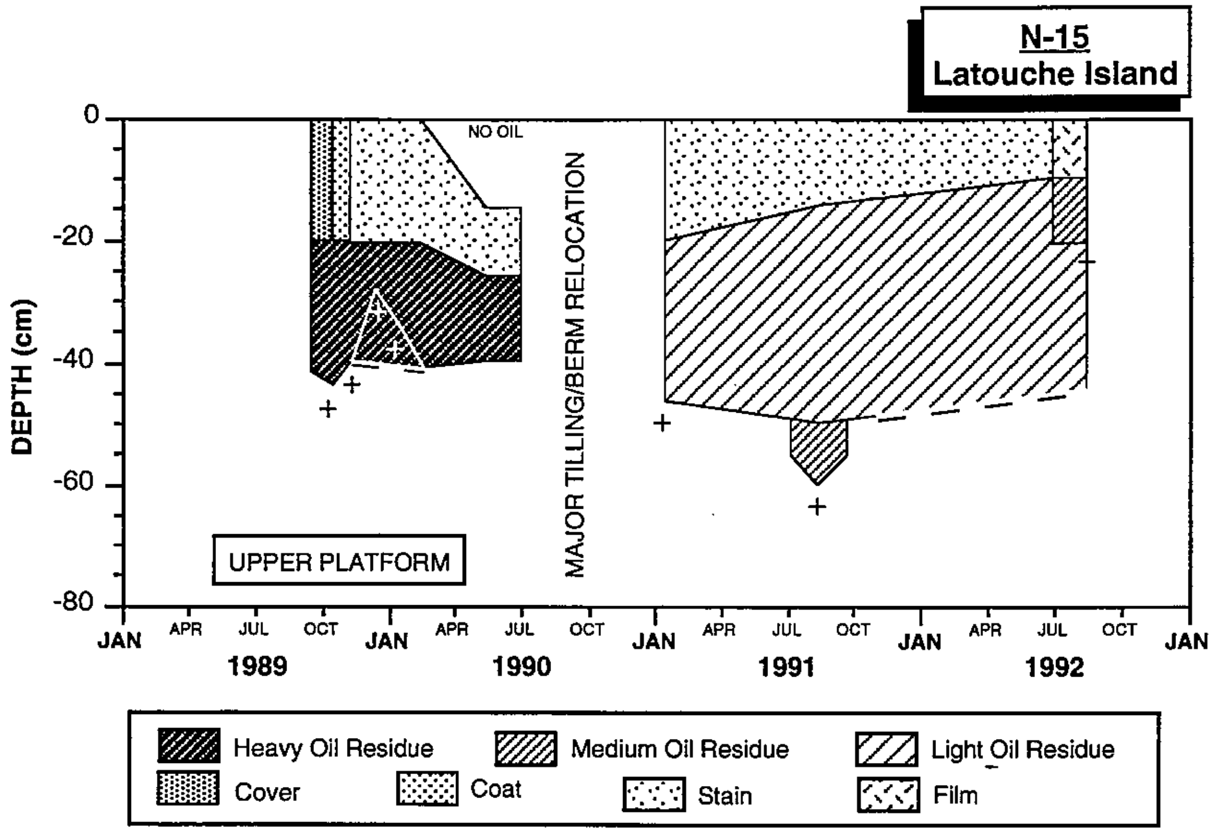


Figure 3-21. Time-series plot of the interval and degree of subsurface oiling at station N-15 (Latouche Island), for the period September 1989 through August 1992. The major tilling/excavation in September 1990 greatly reduced the oil concentration in the upper platform.

Station N-17 (Perry Island)

Introduction. This station is located on a small east-facing pocket beach near the south end of Perry Island, and, because of its easterly exposure, it is subject to considerable wave action. The surveys of this station were halted during the 1990 summer season because of an eagle nest located nearby. It has been surveyed eight times, including during both of the 1991 surveys and during the August 1992 survey.

This beach is similar morphologically and sedimentologically to the other stations classified as cobble/boulder platforms with berms. Erosional/depositional cycles of the high-tide berms have been clearly discernible throughout the survey.

At the end of the eagle nesting season in 1990, a berm-relocation project was carried out at this site. However, by the time of the 20 January 1991 survey, the sediments disrupted by the berm relocation process had been completely returned to their normal configuration along the beach profile. This rapid recovery is thought to result from the facts that: 1) the relocation was limited to the high-tide berm area; 2) high wave activity occurs on this easterly exposed beach; and 3) the pebbles and small cobbles are relatively uniform in size.

Subsurface oil. The trend in the interval and degree of subsurface oil at station N-17 is listed in Table 3-6. No figure was generated because of the limited number of station visits. At the zone of high-tide berms, moderate amounts of oil had penetrated to 45 cm in September 1989. The predominately pebble berm was highly mobile over the winter, showing vertical changes of up to 50 cm between surveys. Large amounts of algal detritus were commonly intermixed in the berm, and the detritus was sometimes spotted with oil. During the September 1990 survey, lightly oiled sediments were overlain by 25 cm of clean sediments, due to the presence of a new spring berm being built from the relocated sediments, as expected in the project plan. However, in January 1991, these new berms were eroded, exposing the underlying oiled sediment layer, which was, coincidentally, 45 cm thick. Although no oil was visible in August 1991, some oil stain (as sticky patches) was visible in August 1992. As the spring berms build and erode, oiled clasts continued to be reworked, even through August 1992.

The upper platform showed a very consistent trend of decreasing subsurface oil over time (Table 3-6). Moderate oil in September 1989 went to light oil in December, which then became thinner by September 1990, when the top 10 cm became free of oil. By

January and August 1991, only oil films remained, which were only visible as light sheens on the water table rather than on the clasts. By August 1992 no traces of oil were visible in this zone. It should be noted that none of the relocated sediments were placed on the upper platform during berm relocation activities, and the platform was very stable, showing almost no topographical changes over the 3.5-year period. However, the most important factors contributing to the steady and complete removal of oil from the subsurface are: 1) the steady flow of groundwater from a freshwater lagoon perched behind the beach; 2) the relatively steep slope of the platform (6°); and 3) the very uniform grain size of the gravel in the beach, consisting of almost entirely (95 to 100 percent) of pebbles and cobbles in the oiled zone. Without a fine-grained component of granules and sand, the oil had a much smaller surface area on which to adhere, and the permeability was greatly enhanced, improving the effectiveness of groundwater and tidal flushing. This beach was more like a "normal" gravel pocket beach in terms of its sediment transport patterns and oil distribution and persistence.

Table 3-6. Historical summary of the interval and degree of subsurface oil at station N-17 (Perry Island). Depths are reported in centimeters.

Survey Date	High-tide Berms	Upper Platform	Lower Platform
Sept. 1989	0-45 (MOR)	0-25 (MOR)	No oil
Dec. 1989	0-45 (LOR)	0-30 (LOR)	
Berm-relocation project—summer 1990			
Sept. 1990	25-37 (LOR)	10-32 (LOR)	
Jan. 1991	0-45 (LOR)	15-25 (OF)	
Aug. 1991	No oil	12-45 (OF?)	
Aug. 1992	0-30 (ST)	No oil	

BAYHEAD BEACHES

Introduction

Two of the stations studied, N-15 (Sleepy Bay) and N-14 (Northwest Bay), are classified as bayhead beaches with mobile gravel. Both stations are located at the apex of moderately large bays and both have streams that flow across the beach near the permanent profile. They are different from the stations classified as cobble/ boulder platforms with berms in several ways: 1) the grain size of the gravel is smaller; 2) they do not have shore platforms with armored cobbles and boulders on the surface; 3) they are not exposed to direct wave attack with a long fetch over relatively deep water; and 4) they are significantly influenced by the migrations of the stream channel and its associated delta.

Station N-18 (Sleepy Bay)

Morphology and sediments. The station at Sleepy Bay (N-18) is located at the very south end of the bay, a north-south oriented indention of the north end of Latouche Island (Figure 1-1). The beach at the head of the bay is bisected by a small anadromous stream that supports a run of pink salmon each August. This stream, which has built a small delta, constantly shifts positions, creating significant changes in the profile. The beach is somewhat sheltered, but judging by the way it has changed over time, it is the site of periodic wave action, presumably as a result of its northerly orientation and a northeasterly fetch of 25 km.

The intertidal zone at this station, which has been surveyed 11 times during the study, consists of three morphological subdivisions (Figure 3-22B): 1) high-tide berms, which are constantly changing; 2) stable central ramp, an extremely stable area; and 3) low-tide bars, a zone of bar growth and migration as result of changes at the stream mouth. During the interval between the surveys of September 1990 and January 1991, the high-tide berms were eroded off flat, the whole central portion of the profile was lowered 10 to 20 cm (on the average), and a major bar was built across the lower intertidal zone. The stream channel had migrated approximately 50 m to the east since the previous September, crossing the profile line for the first time during the study. This primarily erosional episode had exposed previously subsurface oil all along the upper one-third of the profile. During the summer of 1991, the beach at the head of Sleepy Bay was subjected to extensive excavation, removing the extremely persistent subsurface oil. Several large piles of rubble and other assorted coarse gravel were left within the intertidal zone. As shown by the plot of the topographic profile in Figure 3-22B, the intertidal zone. As shown by the plot of the topographic profile in Figure 3-22B, the profile line crossed this mounded material during the 28 August 1991 survey. Amazingly, the profile returned to its original configuration during the storm season of 1991-92, as shown by the survey of 14 August 1992 (Figure 3-22B). However, the field sketch in Figure 3-22A and the comparative surface sediment distribution plots in Figure 3-23, which compare data from the survey of May 1990 with that of the August 1992 survey, show that the sediment distribution had not recovered to its original pattern by August 1992. The coarse rubble/boulder debris remained near the original piles. The wave-generated currents that readily transported the finer cobbles and pebbles on this bayhead beach obviously did not have the competency to transport the very coarse material away from the site of the original mounds. This beach will be very slow to return to its original configuration as far as grain-size distribution is concerned. Nonetheless, the resilience shown by this beach to recover its original topography after such extreme modifications is remarkable.

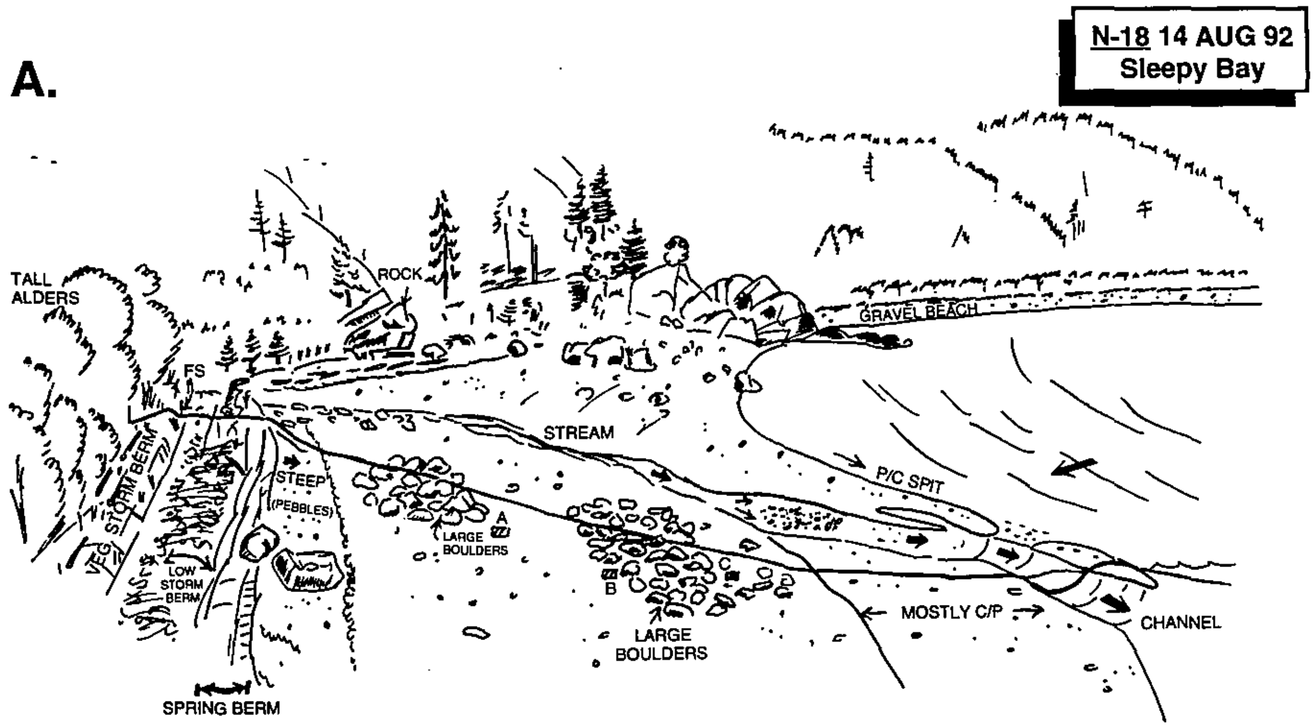
Surface oil. As shown in Table 3-1, the maximum amount of oiling along the profile decreased from readings of 100 percent in September 1989 to five percent in May 1990. However, the newly exposed subsurface oil accounted for surface oiling readings as high as 50 to 60 percent during the January 1991 survey. Estimates of 50 percent stain were made for several survey points on the excavated pile of oiled rubble crossed during the August 1991 survey. However, no surface oil was observed along the profile during the August 1992 survey, another testimony to the effectiveness of reworking of the fine gravel surface sediments by wave action at this site.

Figure 3-22. (Facing Page) Station N-18 (Sleepy Bay).

A. Field sketch on 14 August 1992. Note large boulders on the middle of the profile, left behind as result of major excavation project.

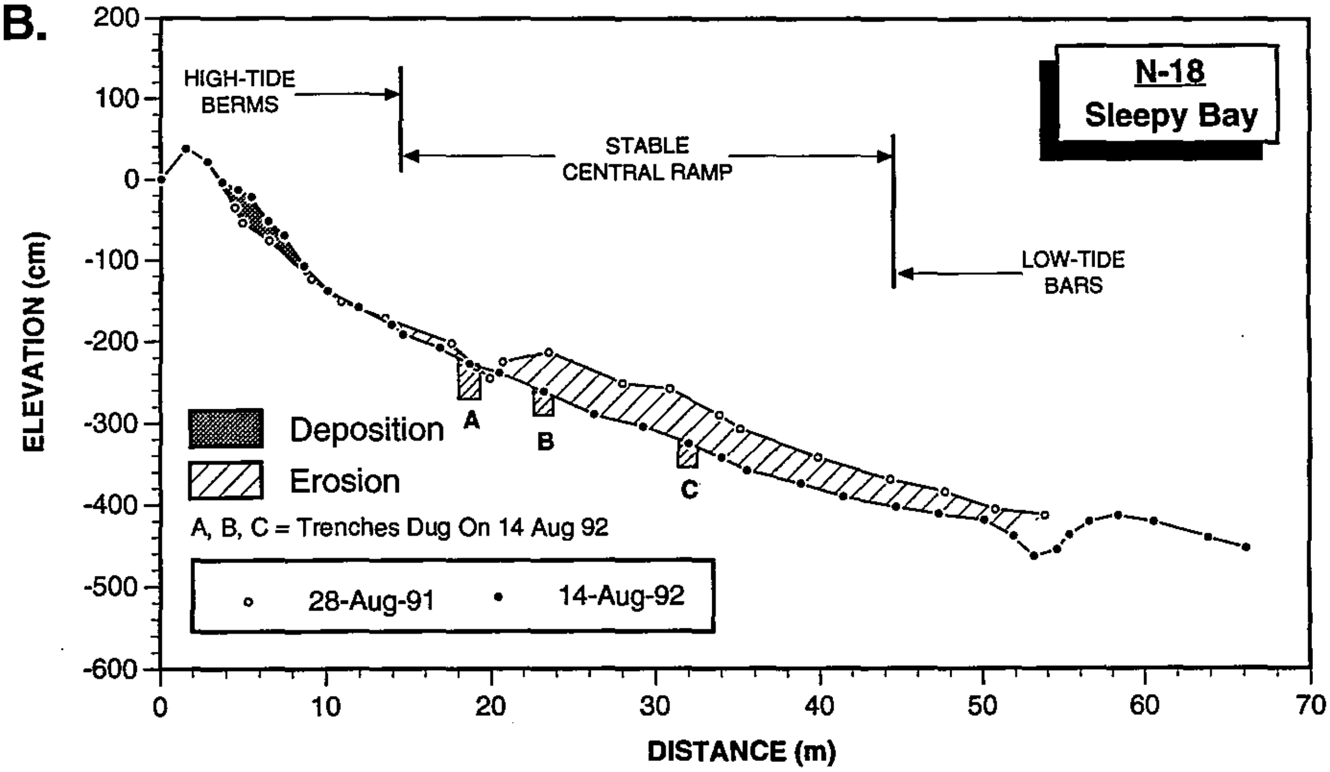
B. Comparison of topographic profiles measured on 28 August 1991 and 14 August 1992. Excavation mound of sediments on the profile in August 1991 was eroded down by wave action during the storm season of 1991-92.

A.



NO OIL OBSERVED IN
TRENCHES OR ON SURFACE
ALONG PROFILE

B.



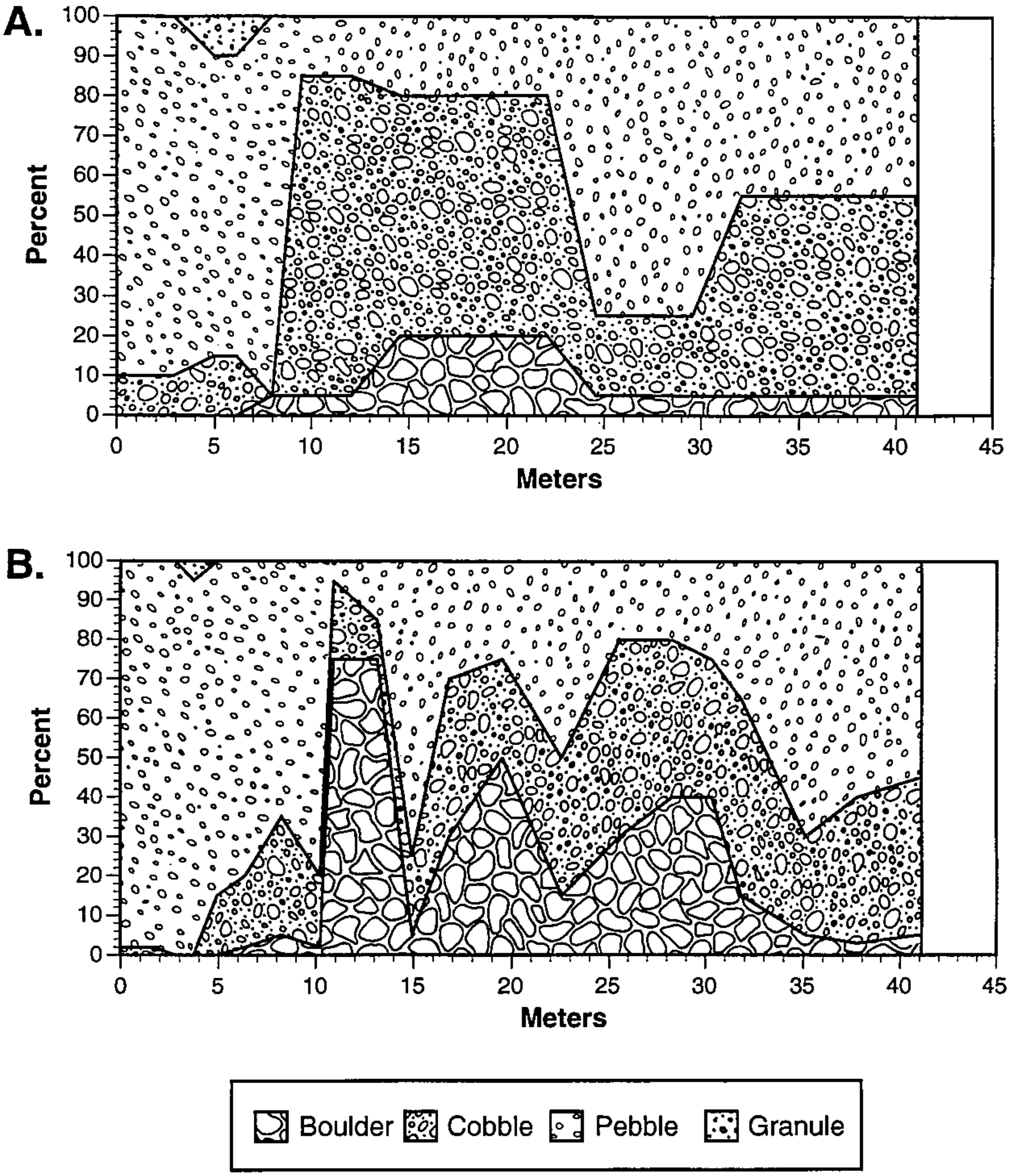


Figure 3-23. Comparison of surface sediment distribution patterns for station N-18 (Sleepy Bay) on: (A) 26 May 1990 and (B) 14 August 1992. Compare plot B with field sketch in Figure 3-22A. The change in the pattern is the result of a major excavation project in the summer of 1991.

Subsurface oil. The history of subsurface oil distribution at station N-18 at Sleepy Bay is listed in Table 3-7 and plotted in Figure 3-24. Sleepy Bay was one of the most heavily oiled areas of Prince William Sound during the spill, probably because it's shape trapped most of the oil that ever entered it. Large amounts of oil had penetrated the pebble berms to depths of more than 50 cm. In fact, oil had penetrated the stream banks (to the west) by more than 125 cm, as found during 1989 excavations with a backhoe.

This heavy subsurface oil proved difficult to remove. Even though the pebble berms were very mobile, the oil had penetrated to depths below that of normal reworking. A detailed discussion of the plot in Figure 3-24A shows this pattern.

The heavy subsurface oil, which was at the surface in September 1989 (before the passage of any significant storm), was covered by a 10-cm high berm of moderately oiled sediments in October. A new, higher spring berm was observed during the November 1989 survey, as shown by 48 cm of lightly oiled sediment; the deeper layer of HOR was not reached by trenching on that date. By the February 1990 survey, there had been net erosion along the profile, and the heavily oiled layer was once again exposed; it remained close to the surface through May 1990. This heavily oiled layer was being actively eroded during the January 1991 survey—patches of coherent oil/sediment were exposed on the surface. After the major sediment excavation of summer 1991, no more oil was observed in the spring berms along the profile. The pebble-sized sediments were readily transported back up the beach, being cleaned of oil in the process. It is obvious that some assistance by cleanup crews was needed to speed removal of the deeply penetrated oil at this site.

A similar pattern of oil persistence can be seen for the sediments of the central ramp (Figure 3-24B). This zone showed very little topographic change in the profile, and the heavily oiled sediments (containing TPH levels of 5,000 to 25,000 mg/kg) remained close to the surface, with little evidence of reworking through January 1991. All five of the trenches dug during the January 1991 survey contained heavy amounts of subsurface oil; a sample collected from a depth of 30 cm in trench B contained 34,000 mg/kg oil, the highest value ever measured at this station.

The extensive mechanical removal of the oiled sediments in the summer of 1991 eliminated much of the remaining subsurface oil (Figure 3-24B). The dug-up rubble and gravel was left in several piles on the beach, one of which was on the survey line (see profile of 28 August 1991; Figure 3-22A).

Table 3-7. Historical summary of the interval and degree of subsurface oil at station N-18 (Sleepy Bay). Depths are reported in centimeters.

Survey Date	High-tide Berms	Central Ramp	Low-tide Bars
Sept. 1989	0-50+ (HOR)	0-50+ (HOR)	0-10 (MOR) 10-40 (LOR)
Oct. 1989	0-10 (MOR) 10-45+ (HOR)	0-15 (LOR) 15-60 (HOR)	
Nov. 1989	0-48 (LOR)	0-5 (LOR) 5-45+ (HOR)	
Dec. 1989	0-20 (LOR) 20-54 (MOR)	0-10 (LOR) 10-58 (HOR)	
Jan. 1990	0-45 (LOR)	0-5 (LOR) 5-50 (HOR)	
Feb. 1990	0-30 (MOR) 30-60 (HOR)	0-30 (LOR) 30-44+ (HOR)	
May 1990	0-3 (LOR) 3-11 (HOR) 11-43 (LOR)	0-32+ (HOR)	
Sept. 1990	0-32 (LOR)	0-10 (ST) 10-33 (HOR)	
Jan. 1991	0-5 (ST) 5-32 (HOR) 32-44 (LOR)	0-31+ (HOR)	
Major sediment tilling and excavation project—summer 1991			
Aug. 1991	No oil	20-30 (LOR)/0-15 (MOR)	
Aug. 1992	No oil	No oil	

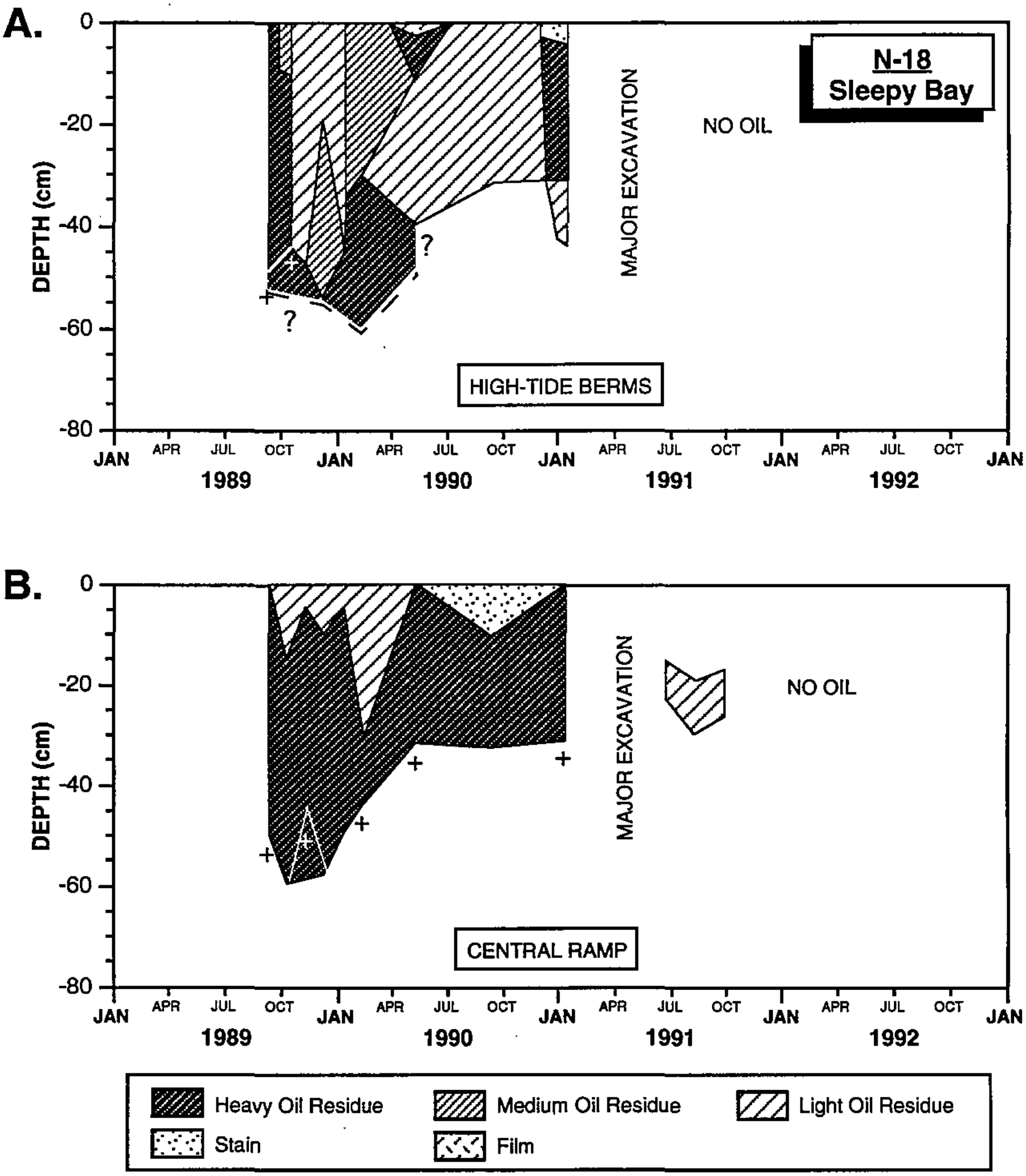


Figure 3-24. Time-series plot of the interval and degree of subsurface oil at station N-18 (Sleepy Bay), for the (A) high-tide berms and (B) central ramp. Note the persistence of heavy oil in both zones until the major excavation project of 1991. No oil was observed during the August 1992 survey anywhere along the profile.

Most of the subsurface oil had been removed from the study site at Sleepy Bay by August 1991, but some remained in the form of light to moderate oil residues. As shown by the plot in Figure 3-24B, only a trace of subsurface oil remained near the mid-tide line, an area noted for very high readings for most of the earlier surveys. No subsurface oil was found in August 1992. Thus, the manual reworking of the heavily oiled mid-tidal zone just east of the stream appeared to be effective.

Station N-14 (Northwest Bay)

Morphology and sediments. This station, which has been surveyed eight times, is located at the head of the west arm of Northwest Bay on Eleanor Island (Figure 1-1). The permanent beach profile is sandwiched between two small anadromous streams which have created a small delta in the low-tide area. The bayhead was uplifted 1.2 m during the 1964 earthquake, thus part of the substructure of the lower part of the intertidal zone is uplifted bay bottom.

This area of the bay, which faces north, is 2.3 km long and has a narrow, 0.5 km-wide entrance. Wave action is probably low-to-moderate during most storms, because of the narrow entrance and length of the bay. However, the sediments are relatively fine-grained, being composed of more than 50 percent pebbles with a generous portion of granules. Thus, even moderate waves generate currents strong enough to move the sediments, particularly in the region of the low-tide bars. The field sketches in Figure 3-25 illustrate changes that have taken place on the beach between May 1990 and August 1992. The mid- to upper-intertidal region, which is a gently sloping, concave-upward surface, has been essentially stable during this period. However, the lower intertidal

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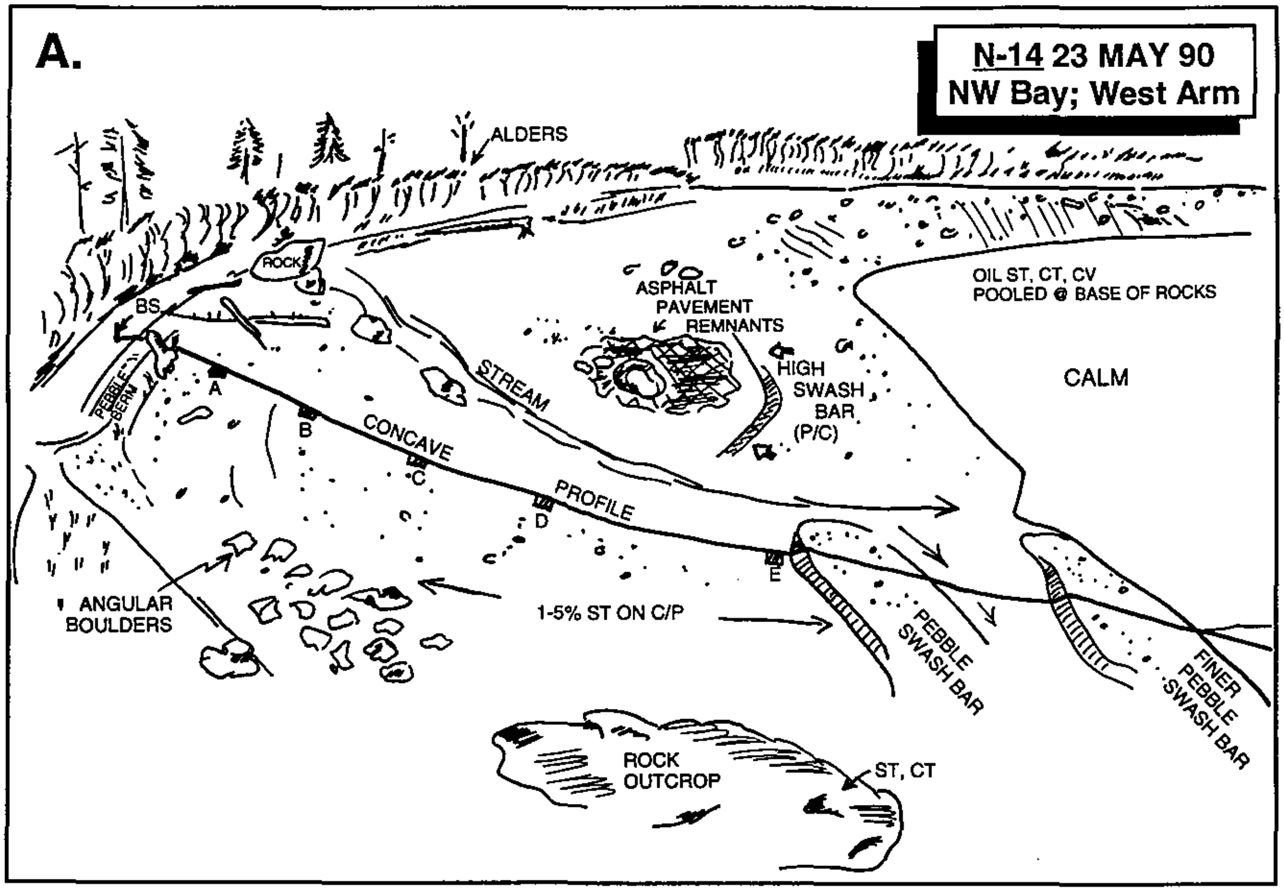
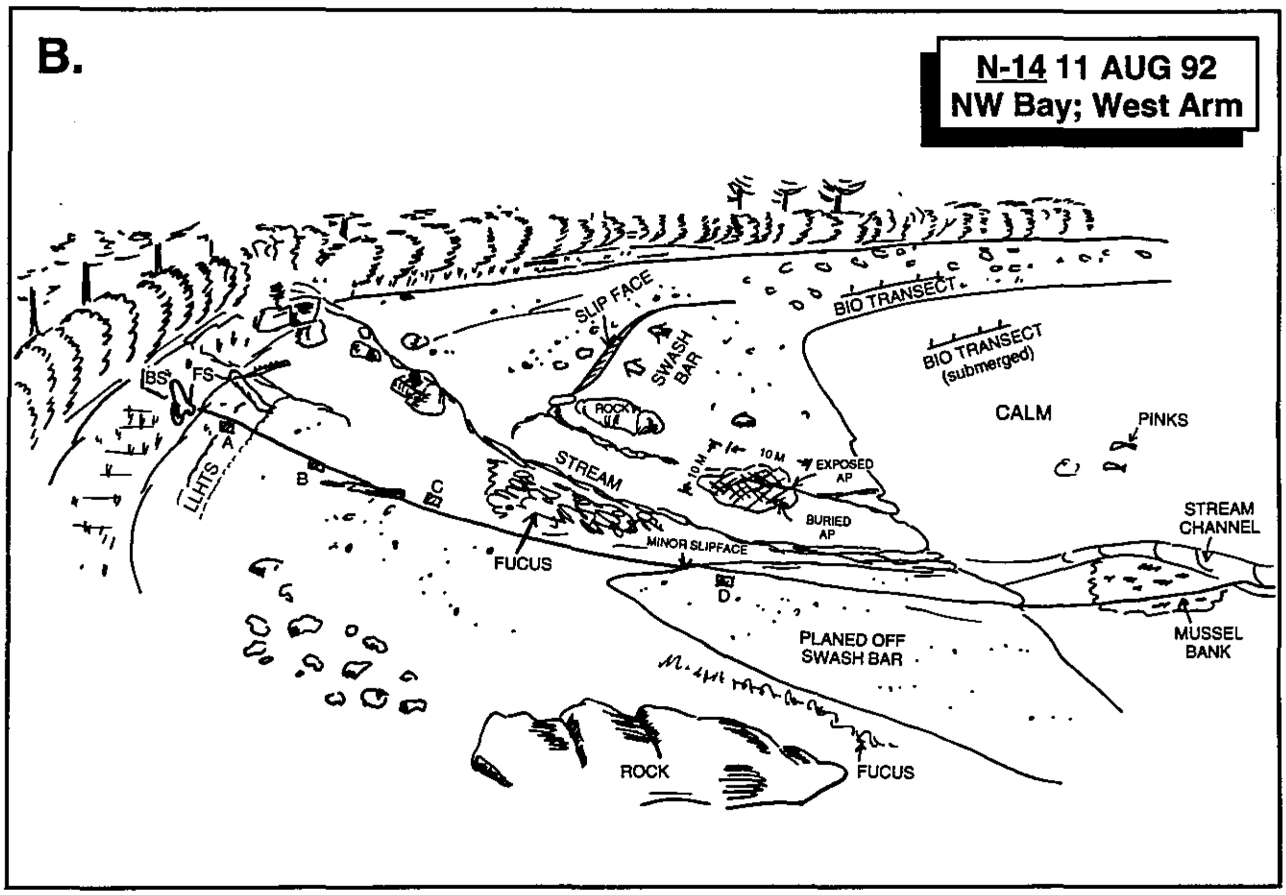
Figure 3-25. (Facing Page) Field sketches of station N-14 (Northwest Bay).

- **A.** 23 May 1990. Profile is concave upward and stable except for landward-migrating lower intertidal swash bars. Note asphalt pavement on west side of stream (manually removed later in summer).

- **B.** 11 August 1992. Note continued landward migration of the intertidal bars. Small distributary on west side of main stream channel has exposed a buried zone of asphalt pavement.


A.
N-14 23 MAY 90
NW Bay; West Arm
ALDERS
ROCK
BS
ASPHALT
PAVEMENT
REMNANTS
OIL ST, CT, CV
POOLED @ BASE OF ROCKS
CALM
HIGH
SWASH
BAR
(P/C)
PEBBLE BERM
A
B
C
D
E
STREAM
CONCAVE
PROFILE
ANGULAR
BOULDERS
1-5% ST ON C/P
PEBBLE
SWASH BAR
FINER
PEBBLE
SWASH BAR
ROCK
OUTCROP
ST, CT


B.
N-14 11 AUG 92
NW Bay; West Arm
SLIP FACE
SWASH
BAR
BIO TRANSECT
BIO TRANSECT
(submerged)
CALM
PINKS
BS
FS
ROCK
A
B
C
D
LLHTS
STREAM
10 M
EXPOSED
AP
BURIED
AP
MINOR SLIPFACE
FUCUS
STREAM
CHANNEL
MUSSEL
BANK
PLANED OFF
SWASH BAR
ROCK
FUCUS

zone has been the site of gradual growth and landward migration of a series of large, intertidal swash bars. This depositional trend on the lower part of the profile is shown by the overlay of profiles measured in January 1991 and August 1992 given in Figure 3-26.

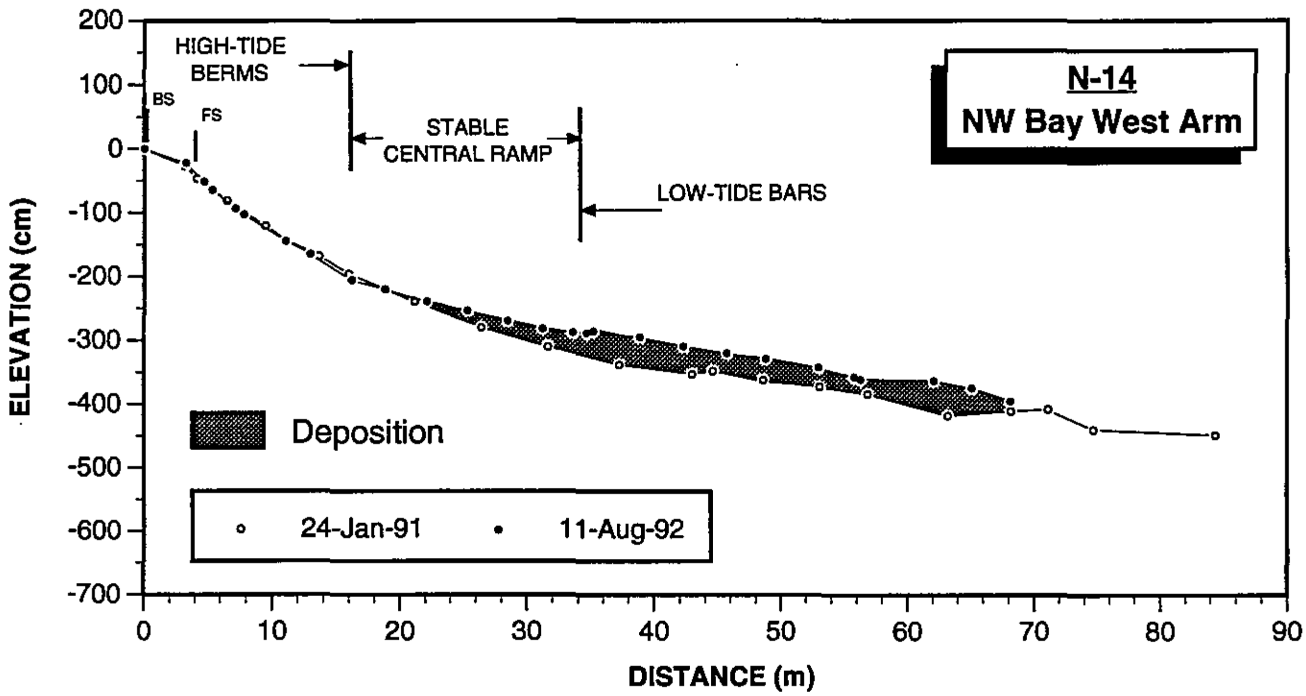


Figure 3-26. Changes between 24 January 1991 and 11 August 1992 along topographic profile measured at station N-14 (Northwest Bay).

Surface oil. The head of Northwest Bay was oiled very heavily during the spill and the beach was treated thoroughly. There was extensive flushing of oiled sediment into the lower intertidal and subtidal zones during the 1989 washing activities, especially at the bayhead (Michel and Hayes, 1991). It is probable that the continued landward migration of the lower intertidal bars shown in Figures 3-25 and 3-26 represents the return of some of the material flushed from the beach during the 1989 cleanup operations to its original position before the spill.

The surface oil had decreased significantly at this site even as early as the first survey in 1989, when a band of 90 percent surface coverage was observed on the stable central ramp. By May 1990, this coverage had been reduced to five percent, and no surface oil was observed on the profile line during the January 1991 survey.

The asphalt pavement by the large rock outcrop on the west side of the stream observed during the May 1990 survey, illustrated by sketch in Figure 3-25A, was removed manually during the summer of 1990. However, as discovered during the August 1992 survey (Figure 3-25B), a 10 x 10 m zone of asphalt pavement had been buried under the large, landward-migrating swash bar on that side of the stream. This mostly buried asphalt pavement was exposed in the channel of a small distributary of the stream which had cut across the eastern side of the bar (Figure 3-25B). This mechanism of burial of oil by the migration of intertidal swash bars was also observed by the authors at the *Amoco Cadiz* and the Gulf War spill sites.

Subsurface oil. No subsurface oil has been observed in the trenches dug along the profile since February 1990, when only small sheens were evident. The extensive washing of the sediments in the 1989 cleanup was very effective at removing the subsurface oil. The depth of oil penetration into the beach was obviously shallow enough to be mobilized during flushing, although this kind of treatment on granule beaches resulted in sediment transport into the lower intertidal and subtidal habitats. The sediments deposited on the lower intertidal zone are returning to the beach in the form of the swash bars, but the fate and effect of the sediments deposited in deeper water is unknown. The biological monitoring studies being conducted by NOAA at this site have suggested that hydraulic flushing resulted in direct mortality, reduced growth rates, and slowed recolonization of nearshore infauna because of the loss of fines and organics in the translocated sediments, direct burial, and elevated levels of oil contamination (Houghton et al., 1992). We concur with these conclusions.

PEBBLE BEACH/TIDAL FLATS

Introduction

There are a number of sheltered pebble beaches with associated tidal flats scattered throughout the study area. Wave energy is relatively low in these areas, with the pebbles at the high tide zone being mobilized by the occasional storm. The sediment veneer is usually quite thin, with peat being a common substrate under the sediment cover. The tidal flats typically have a rich biological assemblage, including clam and eelgrass beds. Two of the NOAA permanent stations located on shorelines of this type—station N-9 on Block Island and station N-11 on Crafton Island—were surveyed in August 1992.

Station N-9 (Block Island)

Morphology and sediments. Station N-9 is an important site that is part of NOAA's biological monitoring program. This shoreline, which has been surveyed ten times, was uplifted 1.2 m during the 1964 earthquake. Located on a roughly north-south oriented shore of Block Island, the intertidal zone is basically a raised tidal flat surrounded by major rock outcrops with a simple pebble/granule/sand berm on its landward side. The profile surveyed is long and flat, extending nearly 100 m on low spring tides. Pebbles make up 60 to 70 percent of the sediments on the profile, with granule and sand usually averaging 15 to 20 percent. The only morphological or sedimentological change observed on this profile during our surveys was the appearance and disappearance of very small pebble berms along the high-tide line. The water table in the tidal flat is very shallow, and ground water drainage networks develop over the surface of the flat at certain stages of low water.

Surface oil. This area was heavily oiled, and in the summer of 1989, the upper part of the intertidal zone was treated with warm- and hot-water flushing, followed by nutrient addition. The tidal flat was not directly treated, to the best of our knowledge. An asphalt pavement located in a tombolo area behind a large rock outcrop just south of the profile was removed manually in the summer of 1990. The maximum surface oil coverage observed along the profile line during the June 1990 survey was a one percent coat on some cobbles in the mid-intertidal zone. No surface oil was observed during the August 1992 survey, but a search in the surrounding area revealed some surface oil in various sheltered microhabitats and pockets in the adjacent rocky areas, indicating the low level of wave reworking that occurs along this sheltered tidal flat.

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

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

2) There are numerous shallow depressions on the flat, presumably from the diggings of sea otters to collect clams (*Protothaca staminea*). Oil and/or oiled sediments could have accumulated preferentially in these depressions, although they are usually water-filled.

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

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

Once contaminated, natural removal rates have been extremely slow, in spite of the presence of active groundwater drainage across and through the flat. The oil in these sediments showed moderate weathering (see Chapter 5 discussion).

Station N-11 (Crafton Island)

Morphology and sediments. Station N-11, which has been surveyed 11 times, is located near the middle of the west side of Crafton Island (Figure 1-1) on the south side of a small, circular indention of the shoreline. It is a sheltered site, subject to little wave action. This profile has shown no significant changes in its morphology or sediment patterns since the beginning of the survey. A shallow peat layer underlies the upper one-third of the profile.

Surface oil. Although this site was moderately to heavily oiled, countermeasures included only manual removal and bioremediation twice, with Inipol in 1989 and Customblen only in 1990. The distribution of surface oil at this site was difficult to assess. The sediments were dark and organic-rich, and the water table was high. The mid- to upper-intertidal area had a 100 percent surface oil cover during the September 1989 survey. A maximum reading of 50 percent was recorded during the September 1990 survey, but much of the surface area of the intertidal zone was clean. Readings of as high as 25 percent surface oil residue were recorded for the upper intertidal zone in August 1991. However, by the time of the August 1992 survey, the surface of the intertidal zone was essentially free of oil, except for sheens on some groundwater drainage a short distance down slope from the mean high-tide line.

Subsurface oil. In many respects, the subsurface sediments at Crafton were similar to that on the tidal flats at N-9 (Block Island): surface covered by subangular pebbles; shallow peat; and high water table. However, the upper intertidal zone was directly contaminated by stranded slicks, and TPH concentrations as high as 9,000 mg/kg (January 1991) have been measured in the top ±15 cm. In August 1991, TPH values of 140 to 1,500 mg/kg were measured, and dull sheens accumulated on the water table. By August 1992, dull sheens occurred in three of five trenches dug in the upper intertidal zone. A greasy zone at 0 to 5 cm in a trench on the upper beachface contained 10,910 mg/kg TPH, though it was patchy in occurrence. We have never visually observed oil in the lower zone, and TPH levels ranged from 20 to 135 mg/kg. Since this site was not subjected to any kind of washing or flushing, there would not have been any cleanup-related transport of oiled sediment from upper to lower intertidal zones. Based on these comparisons, we conclude that, where the lower intertidal zone is relatively flat and contains fine-grained sediments, there is a greater risk of long-term contamination from washing of the shoreline.

SHELTERED ROCKY COASTS

The sheltered rocky shores in the study area are exemplified by station N-6, which is located on a steep, south-facing protuberance of bedrock near the head of the west arm of the Bay of Isles on Knight Island (Figure 1-1). It is in a very sheltered location and contains some surficial sediment that results from normal bedrock weathering. This station, which has been surveyed seven times, was a set aside and it has provided many insights into the process of natural weathering of oil on a sheltered bedrock shore.

During the August 1992 survey, the following important observations were made:

1) Subsurface oil remained in abundance. Asphalt pavement filled crevices between the larger clasts and was 5 cm thick. Subsurface oil in the finer weathered rock debris occurred as medium to heavy oil residue to depths of 10 to 15 cm; and

2) The tops of the bedrock and large clasts continued to be cleaned slowly. Surface oil coverage was down to 5 to 10 percent asphalt pavement and coat in between the larger clasts in August 1992, as compared with 40 to 45 percent on 31 May 1990.

Another station in the sheltered rocky coast class that was studied, station N-10, is in a much more exposed site than station N-6, being located on the east entrance to Herring Bay, Knight Island (Figure 1-1). This area was heavily oiled, and subsequently it was treated with hot-water flushing in June-July 1989. The area was treated with Inipol and Customblen in 1990, and pockets of heavily oiled sediments around the rocks were manually removed. The permanent profile, which has been surveyed 12 times, is positioned down a gully through a massive bedrock outcrop, and there were numerous cracks and crevices that contained scattered patches of coat and asphalt pavement as late as the August 1992 survey. The maximum percent surface cover of oil recorded during the August 1992 survey was five percent, down from a maximum of ten percent in 1991 (Figure 3-27).

Except at the high-tide line, where a minor tombolo in the form of a pebble berm was developed, the bedrock is very near or at the surface throughout the profile. The tomboloid berm was saturated with oil, and the oiled pebbles were removed manually in the summer of 1990. Subsequently, no subsurface oil has been reported on this profile.

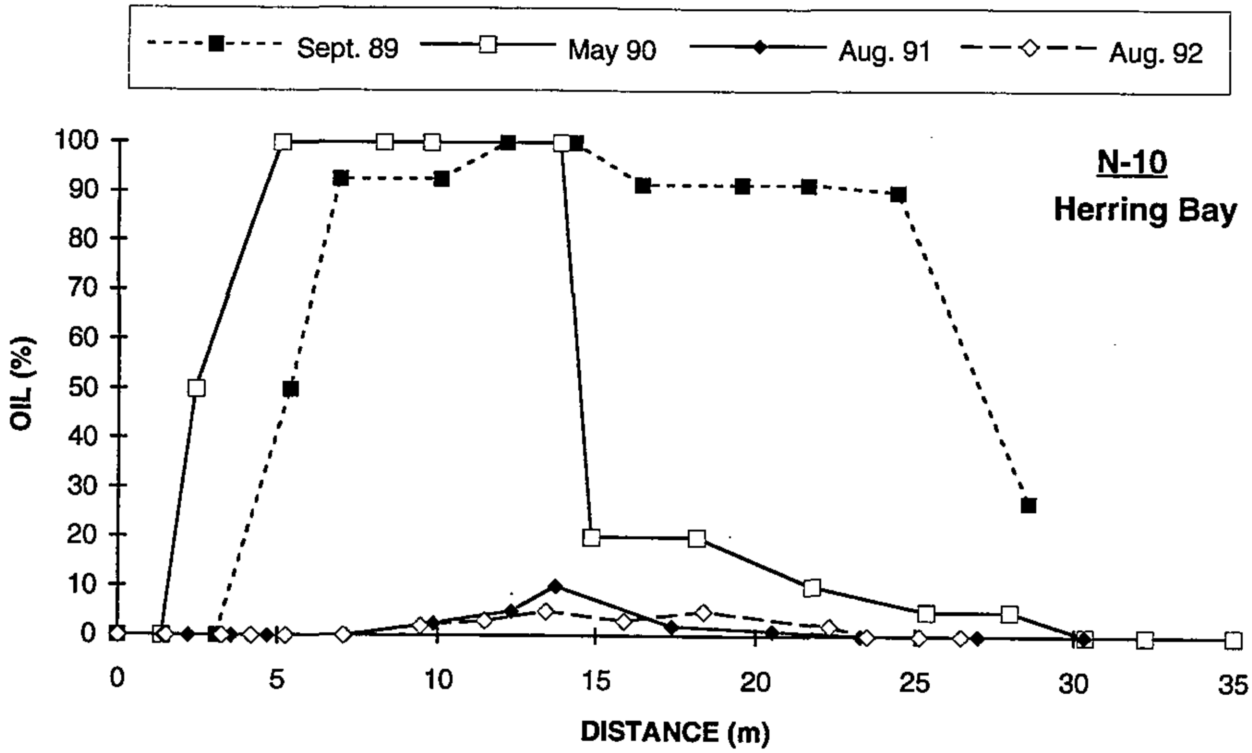


Figure 3-27. Changes in surface oiling coverage over time (1989-1992) at station N-10 (Herring Bay).

A well-developed pebble beach with multiple high-tide berms is located just to the north of station N-10. In May 1990, our team discovered subsurface oil on this beach at a depth of 62 cm below the surface of the lower beachface (lower intertidal zone). This subsurface oil was considerably closer to the surface, at only 22 cm, when we examined the site in August 1992. A photograph and description of the trench dug 50 m north of the profile line at station N-10 are given in Figures 3-28A and 3-29. A greasy brown oil

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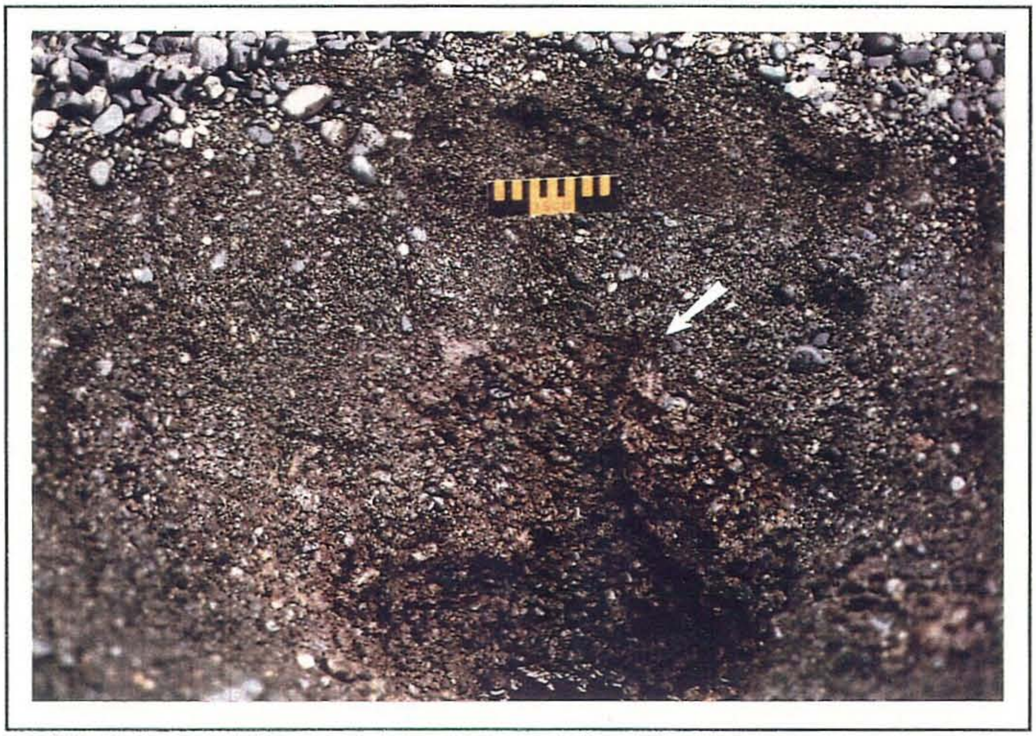
Figure 3-28. (Facing Page) Subsurface oil at trench in pebble beach located 50 m north of station N-10 (Herring Bay).

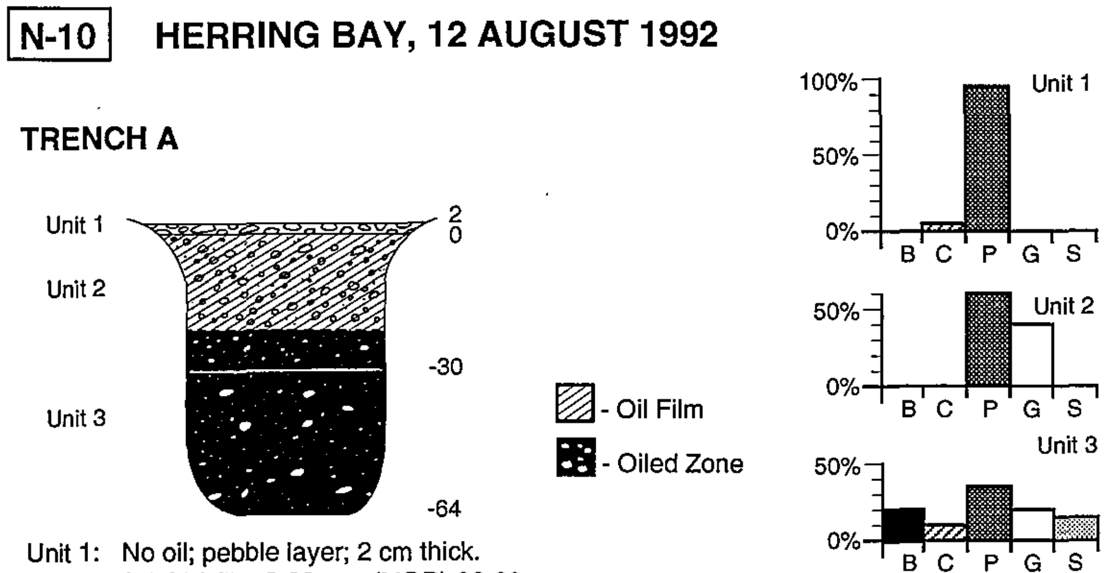
A. Arrow points to the top of the oiled layer at 30-64+ cm depth. Compare this photograph with detailed trench description given in Figure 3-29.

B. Sheens on water surface as result of tide rising to fill trench shown in A.

A.



B.



Unit 1: No oil; pebble layer; 2 cm thick.
Unit 2: (VLOR) film 2-22 cm; (MOR) 22-30 cm.
Unit 3: (MOR) mousse 30-64+ cm (did not reach the bottom of the oil layer); the mousse was greasy and brown in color; minor amounts of clay and organic detritus.

Figure 3-29. Description of trench in pebble beach north of station N-10 (Herring Bay). Compare with photograph in Figure 3-28A.

with the consistency of mousse occupied the pore spaces between the pebbles at depths between 30 and 64+ cm. The bottom of the oiled zone transitioned into a pebble/clay layer. When the tide came up and flooded the open trench, the oiled sediments sheened heavily, as shown by the photograph in Figure 3-28B. A berm-relocation project was carried out in the upper intertidal zone of this beach in the summer of 1990. We do not believe that this deep layer of oil at the toe of this steep pebble beach has ever been reported during the interagency shoreline surveys. This oil layer is most probably the remnant of subsurface oil which originally penetrated all the way from the surface. The beach is composed of unusually uniform pebbles and thus has very high porosity and permeability. Liquid oil could have quickly penetrated these pebbles, even at the lower part of the beach. This site is one of the few areas we have studied in Prince William Sound where oil originally stranded and has persisted in the lower intertidal zone.

ROCKY RUBBLE SLOPES

General Discussion

Station N-13 in Herring Bay (Figure 1-1), another set-aside in a very sheltered environment, is representative of the more protected environments within Prince William Sound that contain sheltered, steeply sloping, rocky rubble shorelines. The coarse-grained clasts that cover the slopes consist of debris that has accumulated on the surface of the slope under the influence of gravity. The clasts show no evidence of reworking, such as sorting or rounding. Because of this mode of formation, the accumulated debris may be permeable enough to allow oil to penetrate several tens of centimeters into the substrate, in contrast to the purely rocky sheltered intertidal zones, such as was described for station N-10. The photograph in Figure 3-30A illustrates the general coarseness and steep slope of the intertidal zone at station N-13. The coarse and angular nature of the rubble, as well as the fine-grained sand and granules that fill the spaces in the substrate, are illustrated by the photograph of trench A in Figure 3-30B, and the trench sketch in Figure 3-31.

Oiling History

There has been a steady decrease of surface oil at station N-13 (Figure 3-32) since September 1989, when maximum surface oil readings of 90 to 100 percent were recorded for the upper intertidal zone. These readings decreased to 30 to 50 percent by the summer of 1990. There was only a trace amount of stain on the protected sides of the large rubble by the time of our August 1992 survey. Unfortunately, we do not have any similar rocky rubble sites in our monitoring program that were treated, to allow comparison of the rates and endpoints of surface oil removal on this shoreline type. It is interesting to note that the surface oil was thicker at this untreated site than the thickness observed during other shoreline surveys. This thicker oil appeared to desiccate, harden, and flake much like dried paint. This oil did not weather by a gradual thinning process; rather it hardened and flaked-off, leaving the underlying rock surface clean. Where the residual oil was thinner, it appeared to weather as stain which persisted in the rock irregularities.

Subsurface oil at N-13 has been very difficult to quantify. There is a shallow water table and the subsurface oil distribution is not uniform. It appears that the oil preferentially penetrated the more permeable zones along the contacts between the rubble and finer-grained matrix. Where the matrix is loosely packed, it also is contaminated. The spatial variability is high; even as of August 1991 two adjacent subsurface sediment samples contained 5,500 and <100 mg/kg TPH. In August 1992, the sediments in trench A (Figure 3-31) described as MOR contained 7,720 mg/kg TPH.

In the field, the oil appears to be relatively unweathered. It sheens readily and is released from the sediments by minor physical disturbances. There is a strong odor and it has a soft, greasy appearance. There have been very little differences discernable over the survey period. Chemically, the subsurface oil at this site shows moderate weathering (see Chapter 5 for discussion).

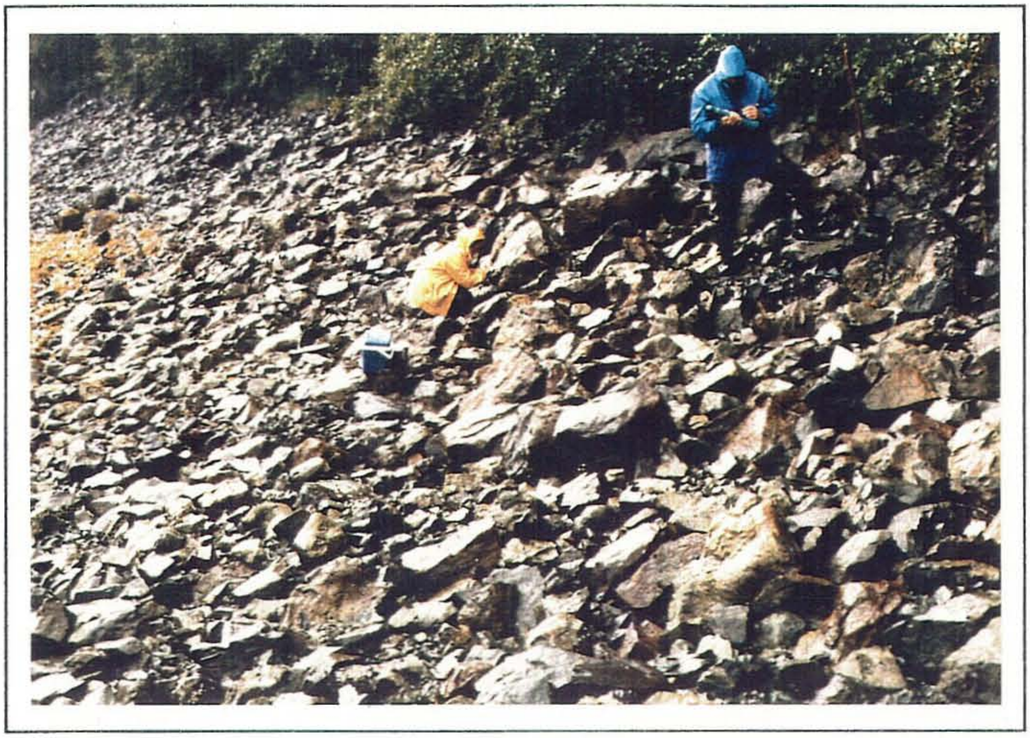
The persistence and slowness of weathering of the subsurface oil is perplexing. There is abundant ground water flow, though it is mostly shallow, in the top 15 to 20 cm. There is a minimum of surface oil residues, such as pavements or patties. It seems the oil either coated the large rubble clasts or penetrated into the subsurface, which is a quite different mode than observed on rocky coasts. In fact, because of these observations of deep, persistent penetration in sheltered rubble slopes, we have devised two classes of sheltered rocky shores in the shoreline ranking system for sensitivity mapping, on the basis of relative permeability. The more permeable rubble slopes should receive higher protection and cleanup priorities because of the potential for long-term persistence, compared to bedrock slopes where the depth of penetration is limited by impermeable bedrock.

Figure 3-30. (Facing Page) Station N-13 (Herring Bay) on August 12, 1992.

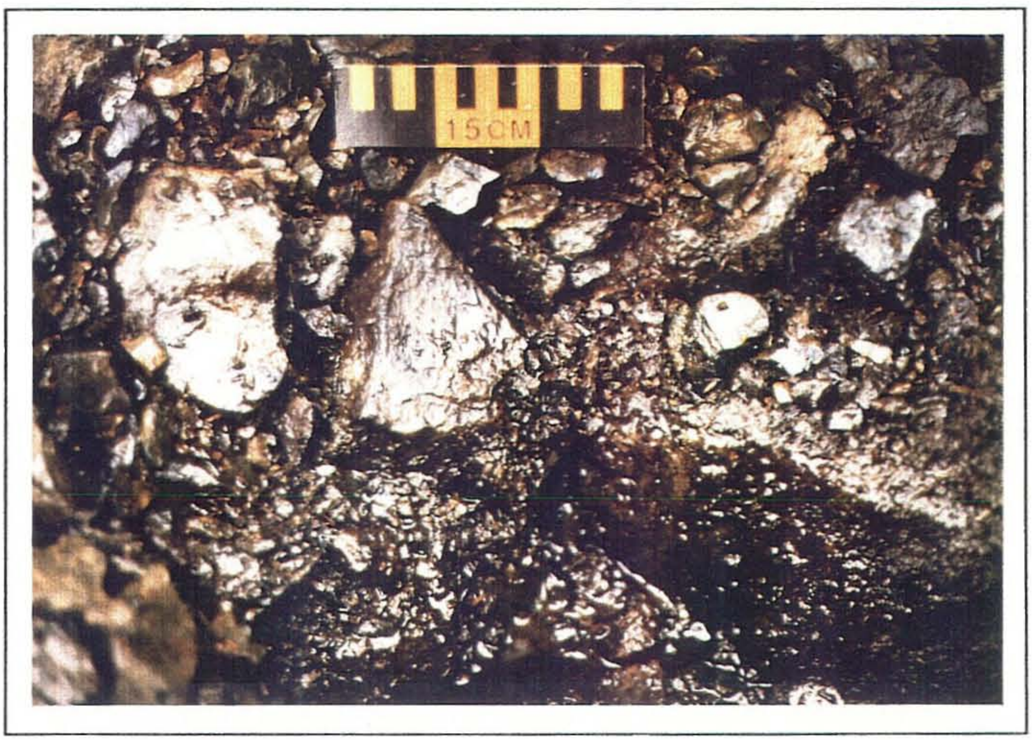
A. Westerly view of intertidal zone. Note clean surface of the angular clasts.

B. Trench A, which was located near the high-tide line.

A.



B.



N-13 HERRING BAY, 12 AUGUST 1992

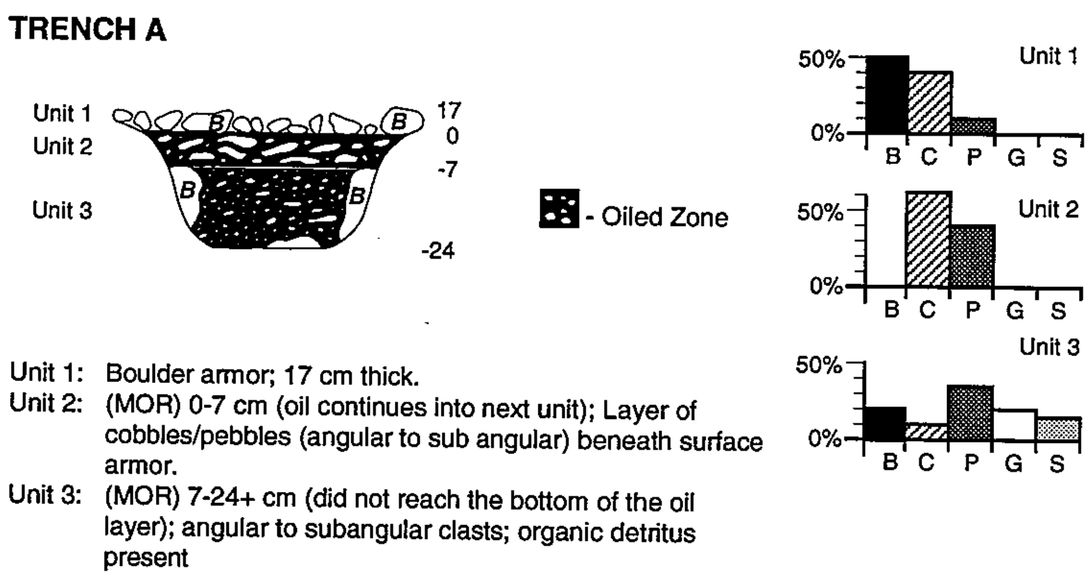


Figure 3-31. Description of trench A at station N-13 (Herring Bay) on 12 August 1992. Compare with photograph in Figure 3-30B.

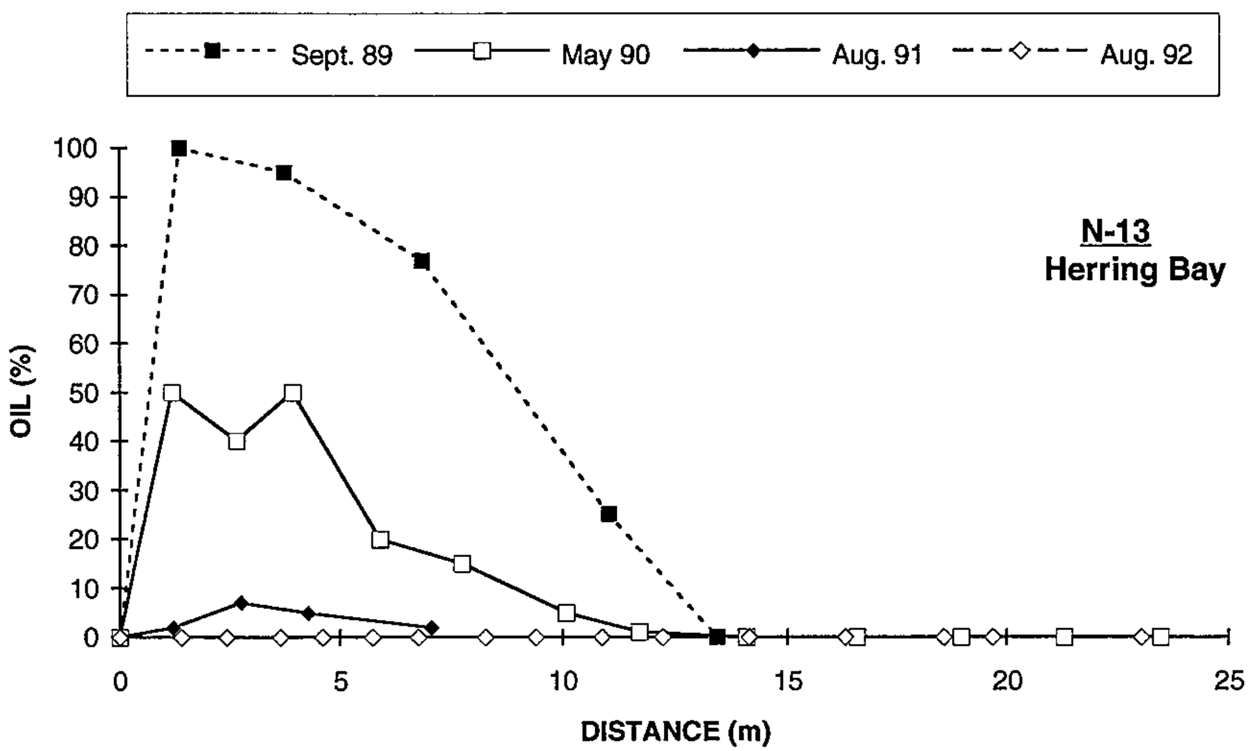


Figure 3-32. Changes in surface oiling (coverage) over time (1989-92) at station N-13 (Herring Bay). Note that no surface oil was observed in August 1992. This site was a set-aside, and thus received no treatment.

ADDITIONAL STATIONS SURVEYED

Introduction

The geomorphology, sediments, and oiling at two new stations, Mussel Beach (MB1 on Eleanor Island) and station ELI-1 on Elrington Island, were described during the August 1992 survey (Figure 1-1). Both stations provide some added insights into the oiling history of Prince William Sound as a result of the *Exxon Valdez* spill. Both sites are included in NOAA's permanent biological monitoring program.

Mussel Beach (Eleanor Island)

Mussel Beach is a tombolo composed mostly of gravel-sized material that connects a small offshore island with Eleanor Island. A sketch map and topographic profile of the tombolo are given in Figure 3-33. This tombolo, which is 70 m long and 50 m wide, is shaped like a saddle. The lowest part of the saddle, on the western side, is covered by a dense growth of mussels.

During the storm season of 1991-92, a scalloped erosional zone was cut into the mussel bed on the northwest side of the tombolo. The eroded scallop, which is 20 m long down the long axis and 13.5 m wide (Figure 3-33A), had a 60 cm-high slipface on the south end that was building on top of the mussel bed. This was the first time such erosion had been observed at this site, so obviously large waves from the northwest are very infrequent. The scallop is a natural event, unrelated to the oil spill. The mussel bed provides some protection from erosion by stabilizing the sediment.

This site is particularly interesting because of the presence of a large amount of subsurface oil below and adjacent to the mussel bed. During 1992, there was concern that the subsurface oil was being held by the overlying mussel bed, and the oil was being bioaccumulated by the mussels. Studies of the natural resource damage assessment program had found elevated levels of petroleum hydrocarbons in mussels and attributed inferred reproductive failures of harlequin ducks and black oystercatchers to chronic exposure to oil via contaminated mussels. One proposed solution was to strip-off the most heavily contaminated mussel beds, so that the subsurface oil could be removed. This site is being studied in detail by the Auke Bay Laboratory of NOAA to evaluate the need for mitigative actions. Our visit was brief, with the objective of physical characterization and evaluation of the erosion.

During our visit, we noticed very light sheens on the north side of the saddle being concentrated at the water line as the tide rose. These sheens were natural, that is, they were not generated as a result of any digging during our survey. Obviously, oil is being released from the subsurface on a routine basis from this site. Sheen samples were collected, and the results are discussed in Henry et al. (In Press).

Station ELI-1 (Elrington Island)

As illustrated by the topographic profile and beach sketch in Figure 3-34, this station also contains a tidal flat/tombolo complex. It is located on the northern tip of Elrington Island in the lee of a small bedrock island. The upper portion of the profile contains a storm berm, a spring-tide berm, and an active beach face., all dominated by pebbles. The middle zone of the profile is a bulge of cobbles that has a ramp-like shape. The lower part of the profile is a tomboloid tidal flat composed mostly of pebbles that has two dense mussel beds on it. Although the shoreline is generally exposed to north-northeast waves, the bedrock islands and headlands provide very sheltered niches. The biology transect is located on the rocky tidal flat and characterized as relatively sheltered.

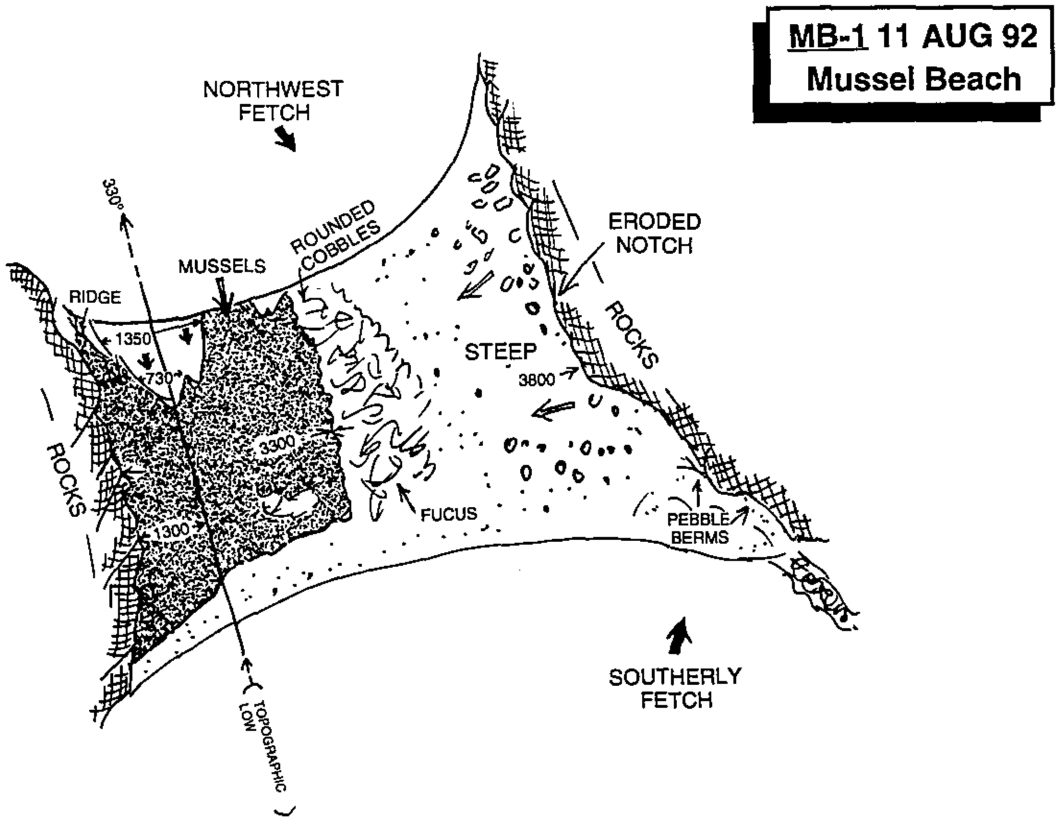
Two distinct patches of oil were still present at the station in August 1992 in the form of persistent, shallow, incipient asphalt pavement/mousse layers underneath a surface layer of cobbles. As the sketch in Figure 3-34B shows, there were two large patches of this shallow mouse/asphalt pavement: 1) one exactly in the lee of the offshore island on the profile line; and 2) in the lee of another large bedrock outcrop to the east of the profile. A sediment sample from the second pavement at 10 to 15 cm depth contained 13,640 mg/kg TPH. Both of these oiled zones straddled the boundary between the middle and upper intertidal zone. We know nothing about the treatment history at this site.

Figure 3-33. (Facing Page) Mussel Beach (Eleanor Island) on 11 August 1992.

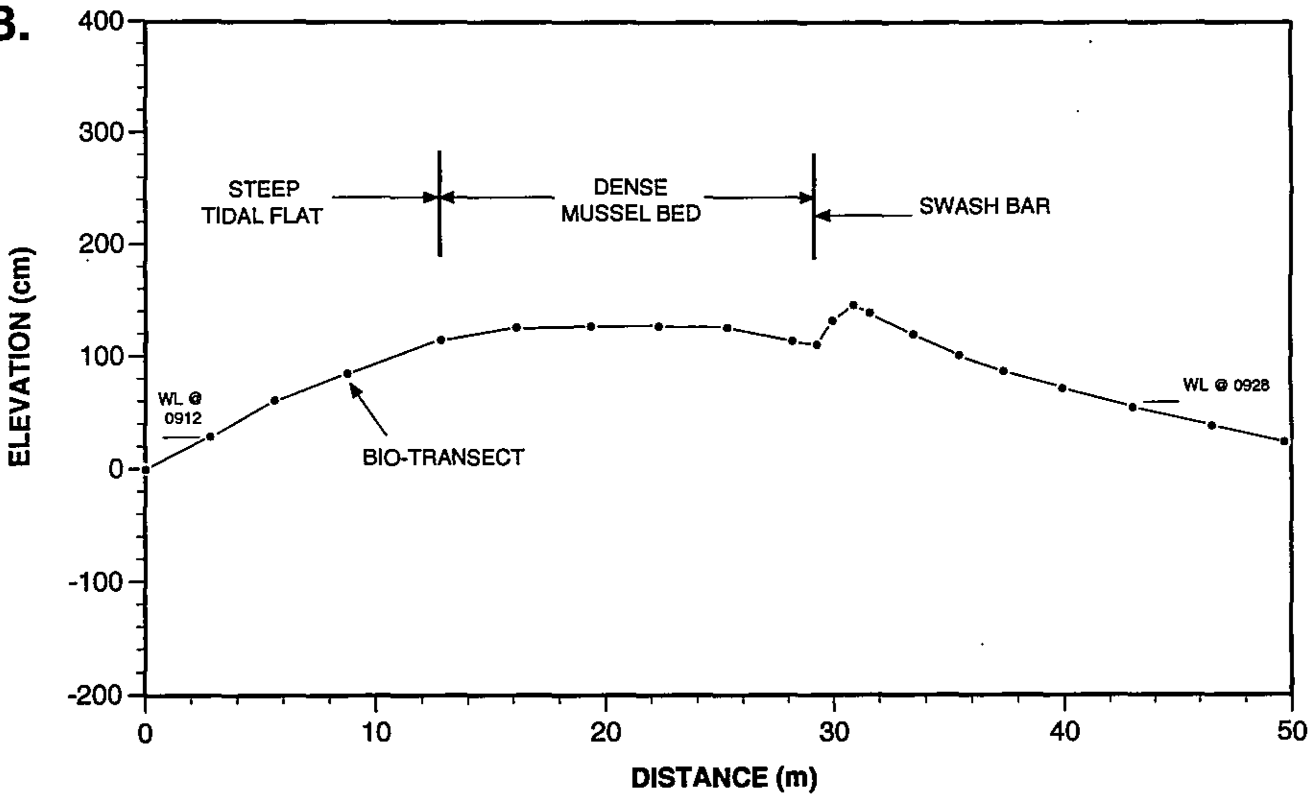
A. Plan view sketch.

B. Topographic profile across the western side of the beach, a tombolo, and through an eroded scallop in the mussel beds on the northwest side.

A.


MB-1 11 AUG 92
Mussel Beach
NORTHWEST FETCH
330°
ROUNDED COBBLES
MUSSELS
RIDGE
1350
730
ERODED NOTCH
ROCKS
STEEP
3800
3300
ROCKS
1300
FUCUS
PEBBLE BERMS
SOUTHERLY FETCH
TOPOGRAPHIC LOW

B.


STEEP TIDAL FLAT
DENSE MUSSEL BED
SWASH BAR
WL @ 0912
BIO-TRANSECT
WL @ 0928
ELEVATION (cm)
DISTANCE (m)
400
300
200
100
0
-100
-200
0
10
20
30
40
50

The residual oil occurred in two very predictable locations—wave shadows on an otherwise moderately exposed shoreline. Obviously, the rounded pebbles on this beach are readily mobilized by waves, but in the wave-shadow areas, only the very surface layer of pebbles are mobile. What surprised us was the consistency of the subsurface oil; it was very soft, brown, and mousse-like. The oil in the sample from the eastern pavement was among the least weathered of the sixteen samples collected in August 1992. We have not found much mousse on gravel beaches in Prince William Sound, even at depth, since 1990. The presence of mousse suggests that there has been no physical disruption of the oil in these areas. The 10-cm surface layer of pebbles is clean, but the 3 to 8 cm-thick mousse/pavement layers nearly fill the pore spaces between the sediments, with a very sharp lower boundary. Eventually, the oil will form asphalt pavements, which have been found to be the dominant form of residual oil on sheltered gravel beaches at numerous large oil spills (Hayes et al., 1990; Fichaut and Poncet, In Press).

SHEENING

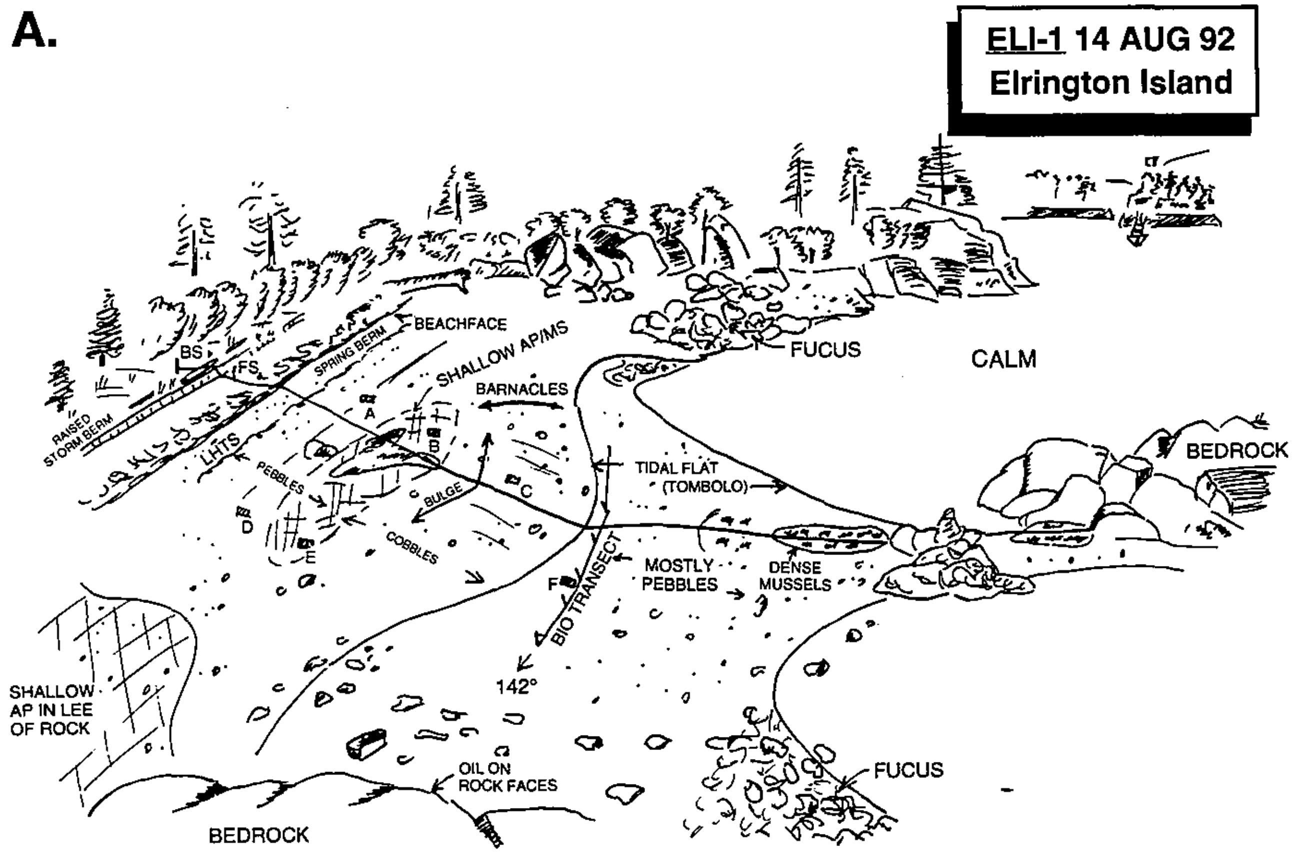
In August 1992, we observed conspicuous sheens emanating from the beach at low tide at two of the stations visited: Smith Island (N-3) and Mussel Beach. The sheens were evident as a thin, iridescent film on the surface sediment (mostly boulders and cobbles) during low tide. As the tide rose, this thin sheen would accumulate into a heavier band at the water line (during calm weather). Furthermore, oiled sediments dug from the subsurface from N-3, N-9, N-10, and N-13 sheened readily when placed in the water. Three and a half years after the spill, the oiled sediments still sheen readily anywhere that the subsurface sediments are even moderately contaminated. This is contrary to predictions made by some authorities during the rock-washer debate in the summer of 1990 (NOAA et al., 1990). Samples of sheens from N-3, N-9, and Mussel Beach were collected for chemical characterization.

Figure 3-34. (Facing Page) Station ELI-1 (Elrington Island) on 14 August 1992.

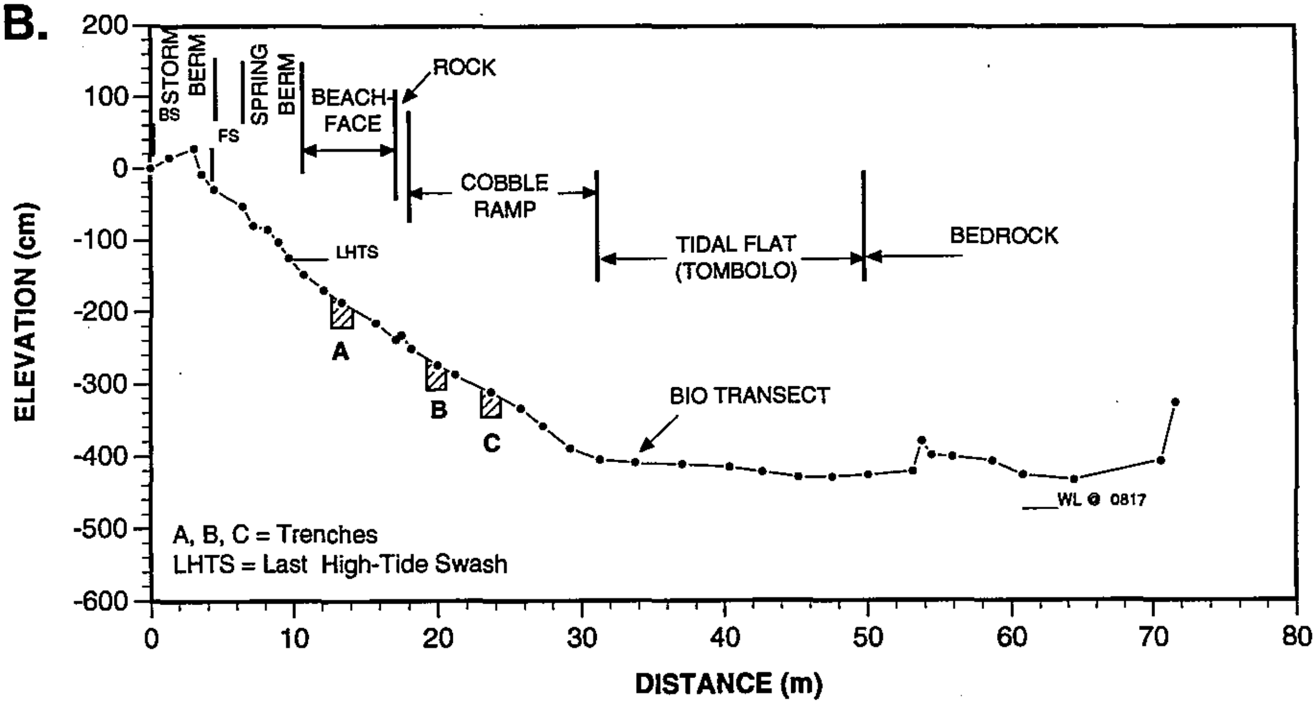
A. Field sketch.

B. Topographic profile.

A.


ELI-1 14 AUG 92
Elrington Island
BEACHFACE
SPRING BERM
SHALLOW AP/MS
BS
FS
RAISED STORM BERM
LHTS
BARNACLES
FUCUS
CALM
BEDROCK
PEBBLES
BULGE
COBBLES
TIDAL FLAT (TOMBOLO)
MOSTLY PEBBLES
DENSE MUSSELS
BIO TRANSECT
142°
SHALLOW AP IN LEE OF ROCK
OIL ON ROCK FACES
FUCUS
BEDROCK

B.


STORM BERM
BS
FS
SPRING BERM
BEACH-FACE
ROCK
COBBLE RAMP
TIDAL FLAT (TOMBOLO)
BEDROCK
LHTS
A
B
C
BIO TRANSECT
WL @ 0817
A, B, C = Trenches
LHTS = Last High-Tide Swash
ELEVATION (cm)
DISTANCE (m)
200
100
0
-100
-200
-300
-400
-500
-600
0
10
20
30
40
50
60
70
80

SUMMARY

For the most part, exposed shorelines of Prince William Sound had been cleaned of surface oil by August 1991. Even in the most sheltered locations, significant decreases in surface oil were noted. Subsurface oil, on the other hand, remains in relative abundance in a number of localities, particularly under the armored surfaces of exposed cobble/boulder platforms with berms, and in the subsurface sediments of the sheltered rubble slopes.

CHAPTER 4
VALIDITY OF BERM RELOCATION AS A SPILL-RESPONSE TECHNIQUE

At the conclusion of our August 1991 survey, we reached strong positive conclusions regarding the use of berm relocation as a spill-response technique, which, in a general way, agreed with conclusions made by Exxon (1991) in their report on berm relocation at 30 sites throughout the *Exxon Valdez* spill site in the summer of 1991. The major conclusions we made in our report (Michel and Hayes, 1992) follow:

"Based on our surveys, it can be stated unequivocably that all the berm-relocation sites we studied showed a marked decrease in subsurface oil in the upper intertidal zone over a period of a few months post-berm relocation. The recovery of beach-profile morphology and sediment distribution patterns, as well as rates of oil removal, were highly site-specific. This indicates that as much site-specific data as possible should be gathered before attempting such projects. Nonetheless, there were two general lessons learned regarding future application of the berm-relocation technique based on our studies in Prince William Sound:

1) When only the face of a storm berm or spring and neap berms were excavated and the sediment was placed within the upper intertidal zone, the result was both rapid cleaning of the sediments by wave action and rapid recovery of the beach profile to near its original configuration (few months at most).

2) If a large excavation was carried out which resulted in the total destruction of all high-tide berms and massive volumes of sediment being moved to the middle intertidal zone, as was done at station N-15 in August 1990, recovery of the profile to its original configuration is considerably slower (> one year). This type of relocation does, however, effectively aid in the removal of the subsurface oil. There may be some situations where this technique would be useful."

The results of the August 1992 survey leave us still optimistic but somewhat more cautious about the use of this technique. Our results certainly do not support Exxon's (1991) assertion that "all the sites have been restored to pre-treatment morphology with no net loss of sediment." This definitely has not happened at station N-15 (see Figure 3-

19). We also have serious concerns about the value of the massive berm relocation carried out at Point Helen (discussed above). Of course, that project, executed in the summer of 1991, was not addressed in the Exxon (1991) report.

Some other observations raise questions concerning our original conclusion on the berm-relocation technique:

1) **Was it really worth the costs involved to just remove the relatively small amount of oil from the zone of the high-tide berms?**

   At most sites, the oil had been removed from the top tens of centimeters by normal berm accretion and erosion. Only the deeper oil remained and it would be remobilized by large storm events. Oil still remains in the subsurface of the middle intertidal zone at stations N-3 (Smith Island), N-15 (Latouche Island), and N-1 (Point Helen), sites of significant berm-relocation projects.

2) **Would the upper intertidal zone (high-tide berms) area of the sites where berm relocation was carried out have been cleaned naturally, given one more storm season?**

   This happened at station N-7 (Knight Island) without berm relocation. The high-tide berms are the most mobile part of the beach, where natural reworking was most effective.

3) **How long will it take the beaches at stations N-1 (Point Helen), N-18 (Sleepy Bay), and N-15 (Latouche Island) to return to their original morphological and sedimentological configurations?**

   These three areas underwent the most extensive sediment excavation and movement of the areas we studied in the Sound, because they had persistent, deep oil. Erosion is not of particular concern here, but it should be noted that the sediments have not stabilized at these sites. During the rock-washer debate, there was much discussion about the effect of the rock washer on beach sediment destabilization on intertidal biota (NOAA et al., 1990). Even at the most disturbed sites, there has been no noticeable biological damage. The NOAA biology monitoring program reported no changes in intertidal biota at N-1, N-3, or N-15 that could be related to berm relocation at these sites (Houghton et al., 1992). It should be noted, however, that in Prince William Sound, the upper intertidal zone on gravel beaches is mostly abiotic, with rich biological communities restricted to the lower intertidal zone. In other locales and settings, where the biological communities extend higher up the beach face, berm relocation could have negative biological effects.

4) **Under what conditions will the transport of fine-grained (and oiled) sediment into the lower intertidal and shallow subtidal be of concern during berm relocations?**

   At the berm relocation sites in Prince William Sound, most of the subsurface oil was associated with the granule and small pebble component of the subsurface sediments, which constitutes a relatively small fraction of the sediments. When these sediments are exposed during berm relocation, they are readily transported by wave action—the coarse material typically is transported landward, and the fines move offshore. In most cases, however, the "finer" sand to pebbles are quickly transported back up the beach by constructive wave activity. The abrasion during transport cleans the grains of any oil. Therefore, transport and penetration of oiled sediments to lower zones is not of great concern on gravel beaches exposed to regular wave activity. However, on mixed sand and gravel beaches, especially those exposed to intermittent wave activity, large amounts of oiled sand could remain in the lower intertidal and subtidal zones, such as observed at station N-14. Most exposed gravel beaches do not have a significant fraction of very fine sediments (i.e., silt and clay) which might result in long-term contamination of subtidal areas.

We must repeat that berm relocation as a cleanup technique has to be evaluated against site-specific conditions. The response of the rather different, armored cobble/boulder platforms with berms in Prince William Sound is more complex than one would expect on a more exposed, highly mobile gravel beach where the entire intertidal zone is constantly reworked by breaking waves. The latter type of gravel beach occurs at Ushagit Island off the entrance to Lower Cook Inlet (see Michel and Hayes, 1991; Figure 17). Exxon's (1991) positive results with berm relocation in that part of the spill site supports this assumption.

We still consider berm relocation to be a viable option for use in the treatment of oiled gravel beaches. However, more experimentation with physical models and detailed field measurements of sediment transport mechanisms is needed before we will be able to apply this technique with complete confidence.

CHAPTER 5
OIL WEATHERING COMPARISONS

Weathering of crude oil is a complex process that can be divided into two phases. The initial phase is dominated by loss of the volatile fractions via evaporation, although there is some loss by dissolution and photo-oxidation. This initial phase of weathering of spills on water occurs over a period of up to one week. The second phase of weathering includes biodegradation and additional photo-oxidation, as well as physical removal processes, and it continues for years post spill. During the August 1992 survey, 16 sediment samples were collected and analyzed to determine the concentration of target PAH compounds to characterize the relative degree of weathering 3.5 years after the *Exxon Valdez* oil spill. A detailed characterization of the stranded oil by various physical settings is discussed in Henry et al. (In Press).

Characterization and presentation of weathering-trend data can be accomplished using several formats. In this report, two formats are used:

1) Plots of the concentration of PAH homologues, normalized to C_2-chrysene. This homologue of chrysene is very resistant to weathering and allows comparisons among samples with widely different levels of contamination. Table 5-1 contains the key for the PAH abbreviations used on these plots.

2) Double-ratio plots of homologues of phenanthrene and dibenzothiophene. These plots are particularly useful to compare among samples which have undergone more advanced stages of weathering, including biodegradation.

Figure 5-1 shows comparison of all samples collected in August 1992 and the reference *Exxon Valdez* cargo oil, using double-plot ratios of C_2/C_3 phenanthrene and C_2/C_3 dibenzothiophene. Note that the reference oil from the *Exxon Valdez* cargo plots in the upper, right-hand corner, with both ratios approximately equal to 2. The samples fall into three groupings, as shown in Figure 5-2. The least weathered samples were: deeply buried oil from the upper platform at Pt. Helen (1A); the deeper layer of oiled pebbles in the beach just north of N-10 in Herring Bay [10A(40)]; and the incipient asphalt pavement/mousse on Elrington Island (ELE-E). The most weathered samples were: the oil coat on pebbles from the storm berm at Pt. Helen (1-berm); the subsurface samples

Table 5-1. Key for the PAH abbreviations used on Figure 5-2.

Abbreviation	PAH Name
NAPH	Naphthalene
C-1 NAPH	C_1-Naphthalene
C-2 NAPH	C_2-Naphthalene
C-1-3 NAPH	C_3-Naphthalene
C-1-4 NAPH	C_4-Naphthalene
FLUO	Fluorene
C-1 FLUO	C_1-Fluorene
C-2 FLUO	C_2-Fluorene
C-3 FLUO	C_3-Fluorene
DBTP	Dibenzothiophene
C-1 DBTP	C_1-Dibenzothiophene
C-2 DBTP	C_2-Dibenzothiophene
C-3 DBTP	C_3-Dibenzothiophene
PHEN	Phenanthrene
C-1 PHEN	C_1-Phenanthrene
C-2 PHEN	C_2-Phenanthrene
C-3 PHEN	C_3-Phenanthrene
ANTH	Anthracene
NBTP	Naphthobenzothiophene
C-1 NBTP	C_1-Naphthobenzothiophene
C-2 NBTP	C_2-Naphthobenzothiophene
C-3 NBTP	C_3-Naphthobenzothiophene
FLAN	Fluoranthene
PYRN	Pyrene
C-1 PYRN	C_1-Pyrene
C-2 PYRN	C_2-Pyrene
BaA	Benz(a)Anthracene
CHRY	Chrysene
C-1 CHRY	C_1-Chrysene
C-2 CHRY	C_2-Chrysene
BbF	Benzo(b,k)Fluoranthene
BaP	Benzo(a)Pyrene
PERY	Perylene

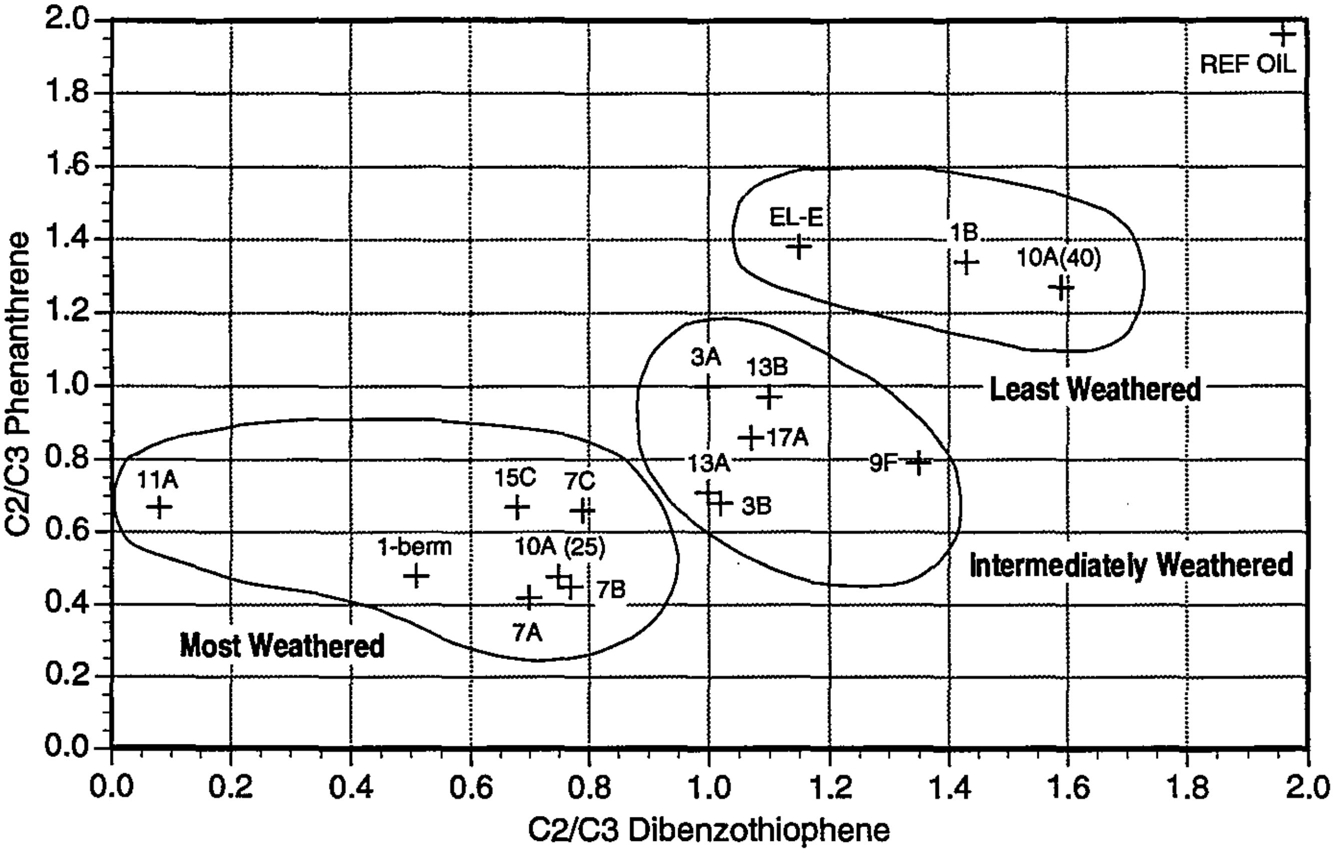


Figure 5-1. Plot of the ratio of C_2/C_3 homologues of phenanthrene versus C_2/C_3 homologues of dibenzothiophene for sediment samples collected in August 1992. The samples have been grouped according to relative degree of weathering. The first number is the station number; the letter is the trench number in Table 2-2.

from three different trenches on the upper platform at N-7 (7A, 7B, 7C); the shallower layer of oiled pebbles in the beach just north of N-10 [10A(25)]; the greasy surface oil layer on the beachface at Crafton Island station N-11 (11A); and the moderately oiled sediment in the extensive area of berm relocation on Latouche Island at N-15 (15C). At an intermediate weathering degree were: moderately oiled sediments from the two trenches on Smith Island at N-3 (3A, 3B); the tidal flat sample from N-9 near Block Island (9F); the two samples from the rocky rubble substrate at the set-aside N-13 in Herring Bay (13A, 13B); and the subsurface oil from Perry Island at N-17 (17A).

Figure 5-2 shows PAH distributions in samples of subsurface oil from three cobble/ boulder platforms with berms: the least weathered oil from Pt. Helen at N-1, an intermediately weathered oil from Smith Island at N-3, and the most weathered oil

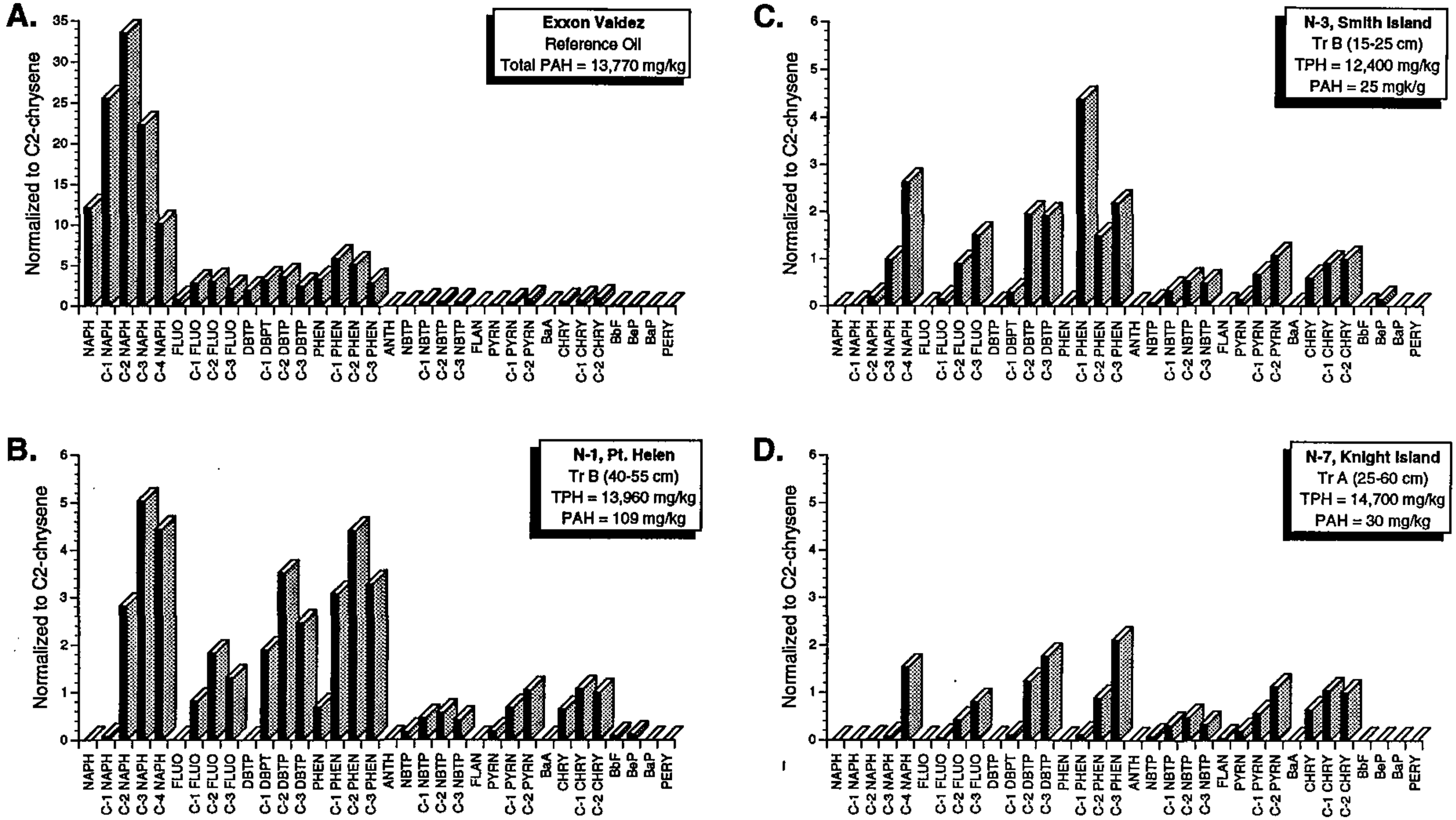


Figure 5-2. Plots of the PAH concentrations, normalized to C_2-chrysene, for the *Exxon Valdez* reference oil and three subsurface samples from cobble/boulder platforms with berms.

from N-7. The *Exxon Valdez* reference oil is also shown. All samples have about the same concentration of TPH (12,400-14,700 mg/kg), but the sample from Pt. Helen has over three times the amount of total targeted PAHs. The subsurface oil at Pt. Helen has undergone only moderate weathering, in that only C_1-naphthalene has been completely lost. There are still significant amounts of C_{2-4}-naphthalenes present, in contrast to the highly weathered sample from N-7, which has lost nearly all the naphthalene and fluorene compounds. The two-ringed PAH compounds (naphthalene and fluorene) are preferentially removed during weathering, compared with the more resistant three-ringed PAHs of concern (dibenzothiophene and phenanthrene).

It is not clear why the subsurface oil at N-7 has weathered so extensively without significant reductions in the TPH concentrations. However, it is important to note that there has been very little change in the weathering degree since 1991. For similar samples from N-7 in August 1991, the PAH distributions were essentially the same (Michel and Hayes, 1991; Figure 45), although there have been decreases in the total PAH concentrations. In fact, there has been very little change in the degree of weathering in samples from all of the stations over the year between the 1991 and 1992 surveys. It appears that the weathering rate has slowed, in all settings. The high concentrations of oil with depth in the coarse-grained sediments remain resistant to physical and chemical removal processes. Where mechanical means were used to physically break up heavy oil accumulations, the oil has weathered more extensively, such as the tilled gravel at N-15 and the relocated storm berm at N-1.

CHAPTER 6
SUMMARY OF OIL BEHAVIOR AND PERSISTENCE BY SHORELINE TYPE

INTRODUCTION

Throughout the 3.5 years of NOAA surveys, different patterns of oil behavior and persistence have emerged. These patterns are complicated by a great diversity in site-specific combinations of conditions, such as grain size and sorting, origin, exposure, and uplift during the 1964 earthquake. In the following sections, general models are described for each shoreline type so that the important processes can be highlighted.

COBBLE/BOULDER PLATFORMS WITH BERMS

The exposed gravel beaches of Prince William Sound have unique characteristics that make them different from what are considered to be "typical" gravel beaches. In fact, we have made a special effort not to refer to them simply as gravel beaches. They are truly cobble/boulder platforms, which have visible pebble/cobble berms forming the upper intertidal zone. The platforms are almost flat (4-6° slopes) compared to the 12-15° slope of the beach faces of the berms. There are two different subclasses: ***Subclass I*** - those that have relatively flat platforms (±4°), relatively thick sediment veneer on the platform, and steeper platforms (±6°), thinner sediment veneer on the platform, and a stable, coarse-grained armor; and ***Subclass II*** - those that have more mobile surface sediments. There are very significant differences in the oil persistence for these two subclasses, as discussed below and shown in Figures 6-1 and 6-2.

The general model described in our 1991 report for the period right after the spill through the summer of 1990 has been revised as shown in Figure 6-1, which describes Subclass I. The initial oil stranding usually covered the entire intertidal zone, because of the accumulation of large slicks against the shoreline and the gentle slope of the platform. However, by the end of May 1989, the oil that had stranded on the surface of the lower platform was lifted off by the tides. The maximum width of heavy surface oiling on most shorelines was 15 to 35 m. Over the summer, spring tides pushed the oil up higher on the beach and over the spring berm, to the base of the active storm berm, if present. In most cases, the oil was not pushed up into or on the active storm

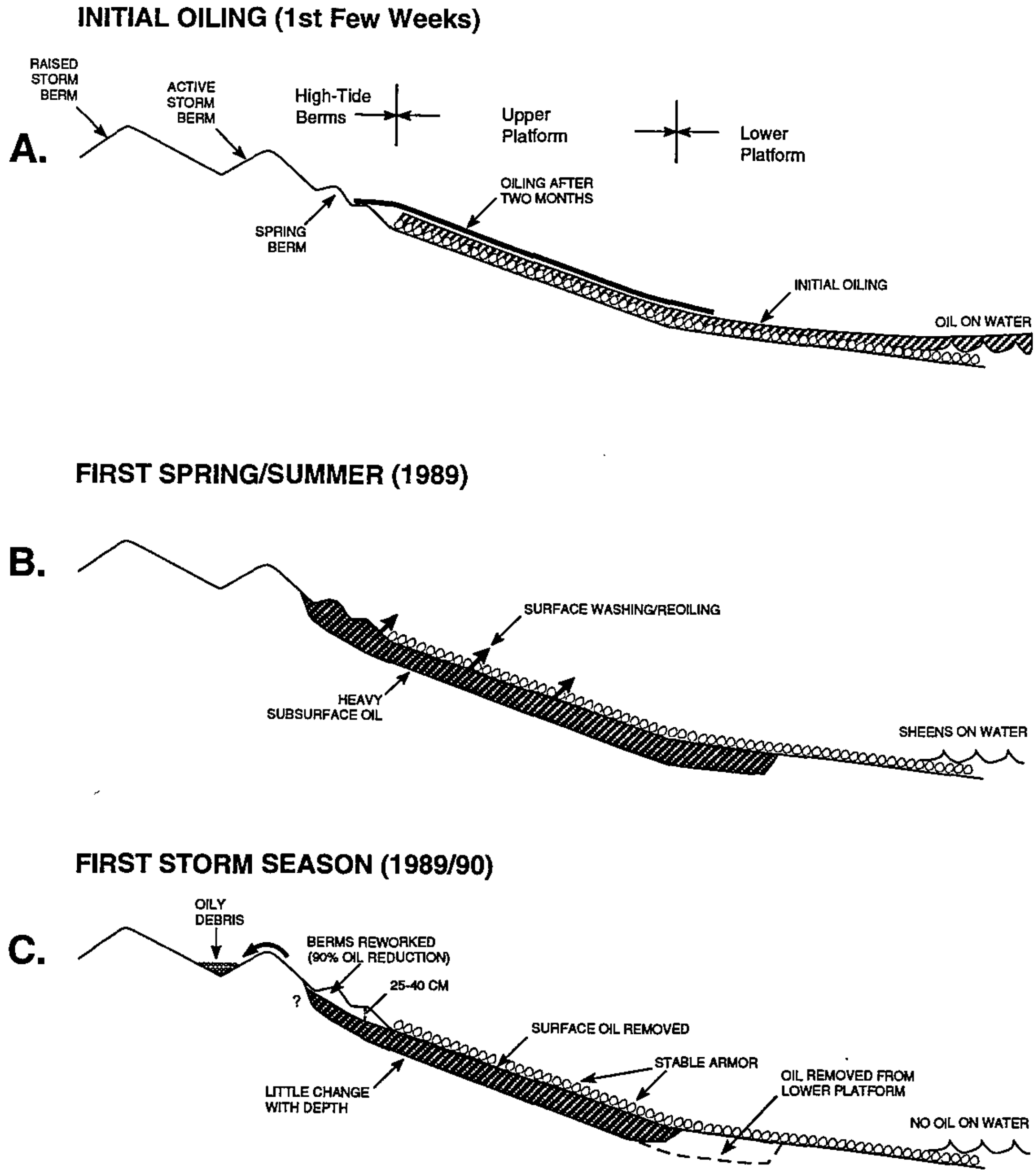
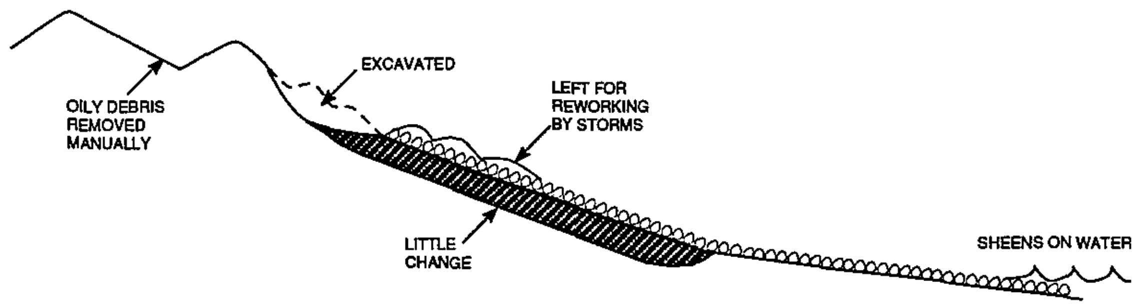


Figure 6-1. Schematic model of the behavior and persistence of oil from the initial stranding to the end of 1992 on cobble/boulder platforms with berms, Subclass I—those with a well-established coarse-grained armor on the platform, relatively flat slope of the platform, and relatively thick veneer of sediments on the rock platform.

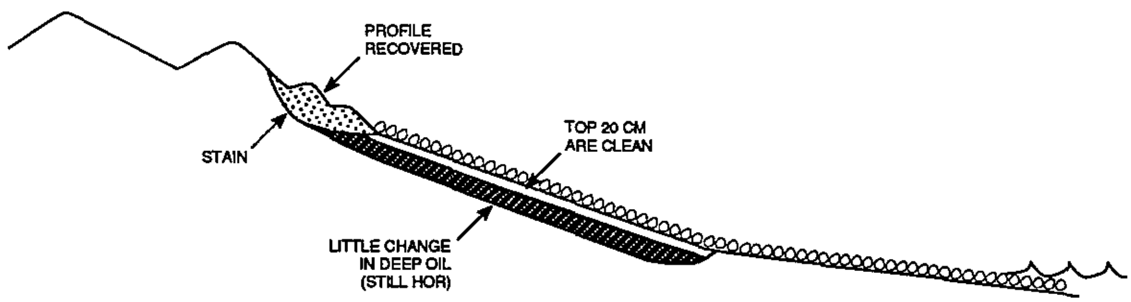
SECOND SUMMER (1990 Berm Relocation)

D.



THIRD SUMMER (1991)

E.



FOURTH SUMMER (1992)

F.

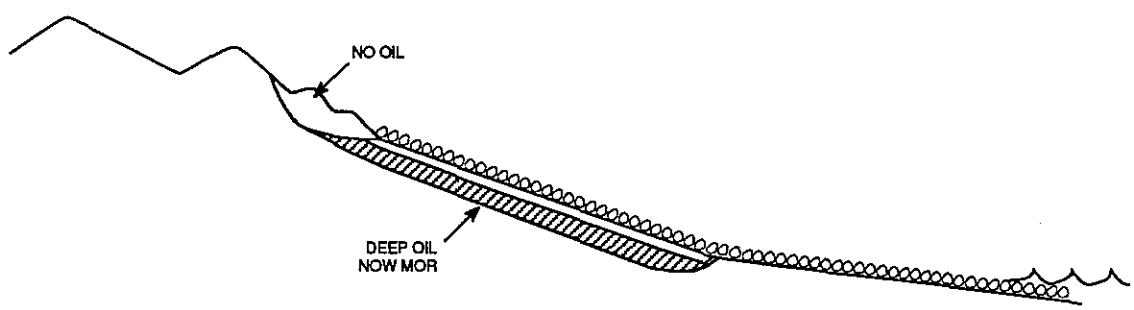


Figure 6-1. cont.

berm, because there were no very large storms during the period after the release when there were abundant heavy slicks on the water.

By mid-summer, there was no longer any oil pooled on the surface; it had all penetrated the porous sediment (Figure 6-1B). The depth of penetration was limited by the volume of oil, the water table, and the presence of an impermeable layer, either bedrock or fine-grained sediments. Because of the coarse-grained nature of the sediments, the depth of penetration in the high-tide berms averaged 75-100 cm, whereas in the upper platform the average depth was about 50-75 cm. The oil was very liquid and mobile, causing many problems with re-oiling after extensive high-pressure flushing.

During the first storm season, the only area of significant oil removal was at the high-tide berms, where erosion and deposition of the pebble/cobble berms reworked the sediments to an average depth of 25-40 cm (Figure 6-1C). In places, any subsurface oil in the lower platforms was also removed. The stable armor on the upper platform effectively immobilized the substrate underlying the armor, and very high concentrations of oil remained after the first storm season ended. Armoring of the platform is a major factor in the fate of oil on this shoreline type. Sediment from the upper and lower components of the shoreline is transported across this platform but the armor remains intact. The only conditions under which the armor will be mobilized is during extreme storm events, such as a ten-year storm. The inherited bedrock platform, which produces a gentler-than-average beach slope, contributes significantly to the formation of armor and the retention of the oil.

During the second summer, the spring berm on some beaches was mechanically relocated to the upper intertidal zone (Figure 6-1D). On many beaches (discussed above), these relocated sediments were returned to their original position over winter, and, as of the third summer, the oil in the spring berms was greatly reduced. There was a significant change in the degree of oiling in the top 20 cm below the armor on the upper platform, but the deeper subsurface oil remained unchanged (Figure 6-1E). By the fourth summer, it appeared that the deep oil had been reduced from heavy to moderate degree of oiling, though there had been no change in the interval of oiling (Figure 6-1F). The beaches at N-1 (Point Helen), N-7 (Knight Island), N-3 (Smith Island), and N-15 (Latouche Island) fall within Subclass I.

The cobble/boulder platforms of Subclass II (shown in Figure 6-2) had a similar pattern up to the end of the summer of 1989. These beaches showed much greater reductions in subsurface oil by the end of the first winter, with mostly light oil remaining (Figure 6-2C). The spring berms on many of these beaches were also relocated (Figure 6-2D), and the profiles showed rapid and very complete return to the original profile (Figure 6-2C). At the end of the third summer, only traces of oil stains and scattered zones of light-to-moderate oil remained in the subsurface. By the fourth summer, these beaches were essentially free of subsurface oil, except for very scattered stain on cobbles. The beaches at N-17 (Perry Island) and N-4 (Smith Island) fall within Subclass II.

SHELTERED ROCKY COASTS/RUBBLE SLOPES

A general model for the distribution and persistence of oil on sheltered rocky coasts is shown in Figure 6-3. These coastlines are characterized by a very thin veneer of sediment, derived in-place from the weathering of the underlying bedrock. This sediment veneer occurs only on the upper intertidal zone; the lower zone is oftentimes bare rock or very large boulders. The sediment veneer consists of pebble- to cobble-size rock fragments with the crevices between the rock fragments and bedrock filled with tightly packed granules and pebbles.

By the end of the first summer, surface oil remained on only the upper half of the intertidal zone (Figure 6-3A), mainly because the lower zone was covered with algae and stayed wet, preventing long-term adherence of the oil. Cleanup reduced the thickness of the surface oil significantly, which sped the weathering and degradation of the oil. Within two years, only traces of surface oil remained, mostly on the sides of bedrock/ boulders and in underrock settings.

In the subsurface, oil had penetrated into the pores of the sediment filling the crevices and under rock fragments, as shown in Figure 6-3B. This crevice oil was partially removed by hot-water washing during 1989; manual removal efforts in 1990 further decreased the amount of oil, which by then had started to form small incipient pavements. The maximum depth of oil seldom exceeded 15 cm, with 5 cm being more common. Although the oil content of these pavements was very high, the amount of oil in these habitats as of 1992 was very small, with estimated coverage usually less than one percent of the total surface area. However, natural weathering of these patches of heavily oiled sediment in crevices had been very slow, with little change except that affected by manual removal or breakup. This residual oil was not mobile and did not generate sheens unless disturbed, and it was located only on the upper half of the

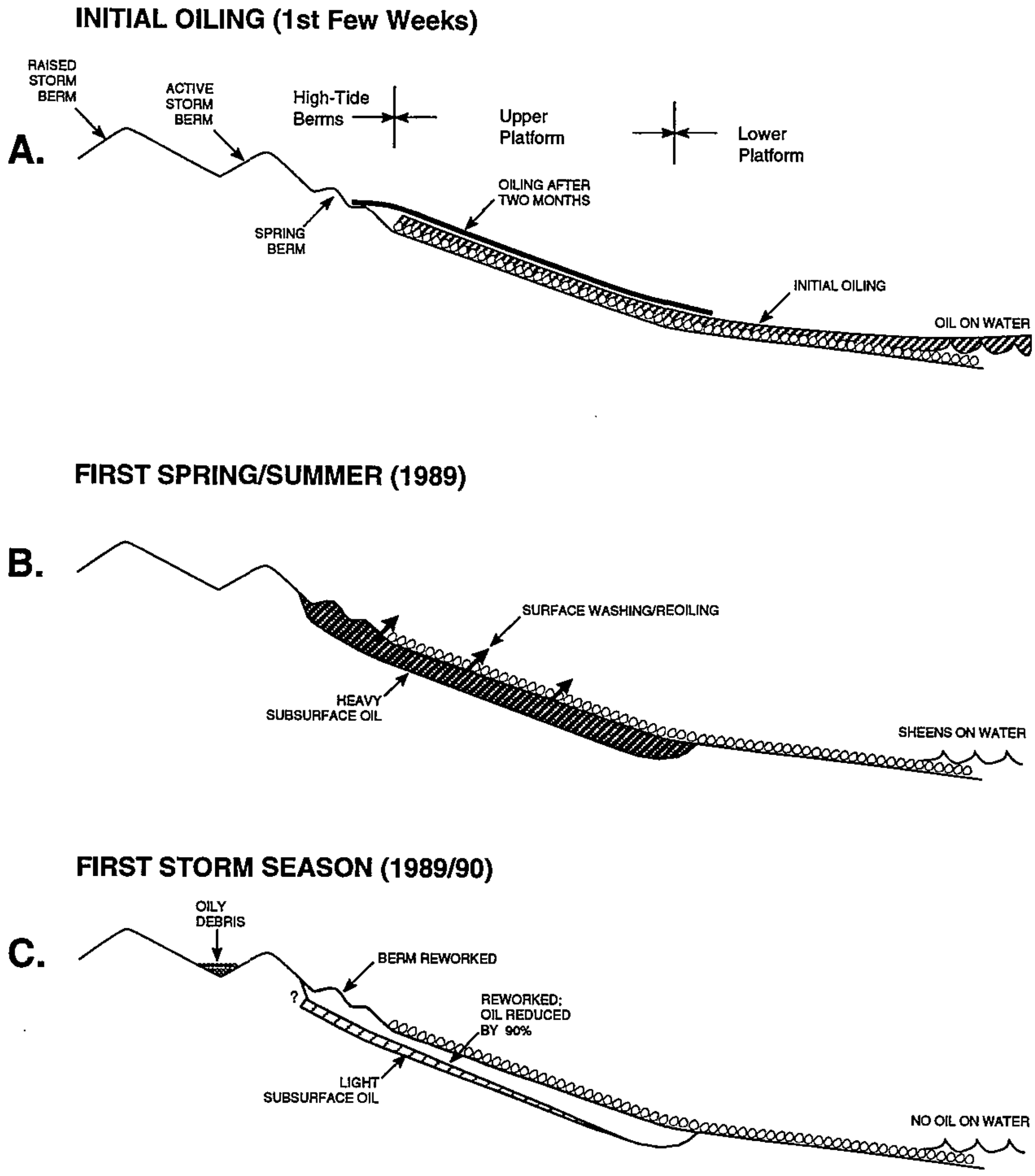


Figure 6-2. Schematic model of the behavior and persistence of oil from the initial stranding to the end of 1992 on cobble/boulder platforms with berms, Subclass II—those with highly mobile sediments, relatively steep slope of the platform, and relatively thin veneer of sediments on the rock platform.

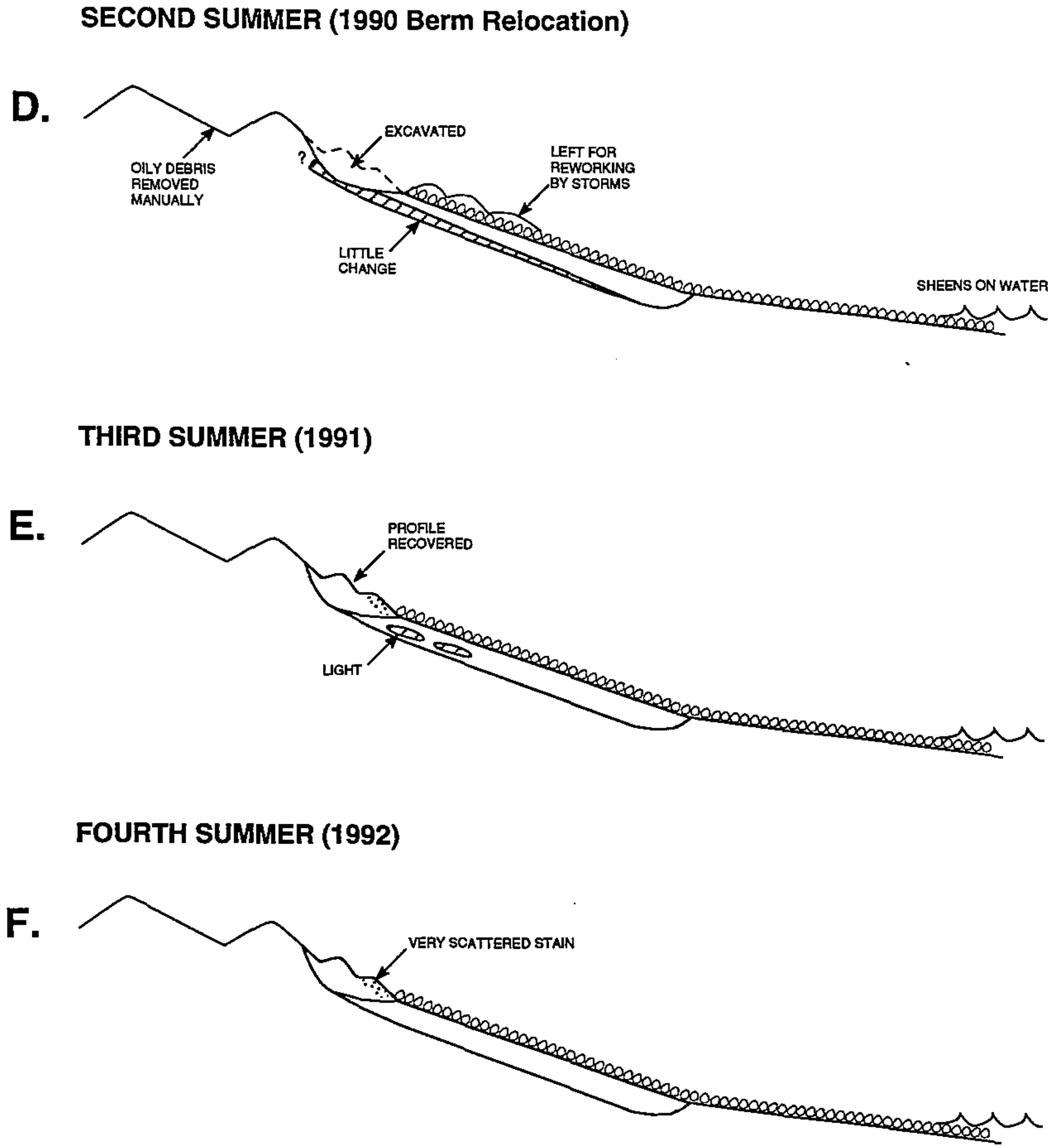


Figure 6-2. cont.

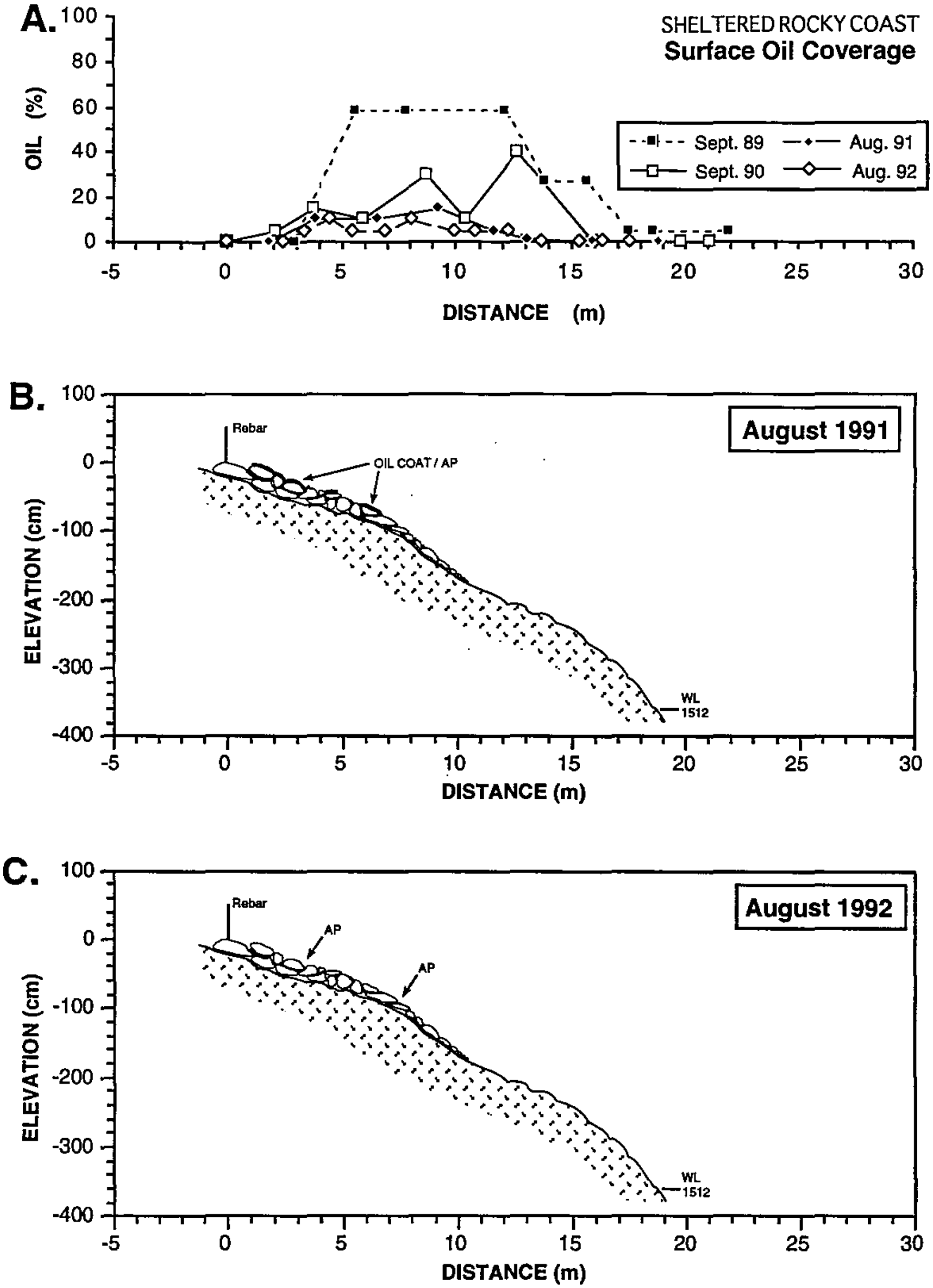


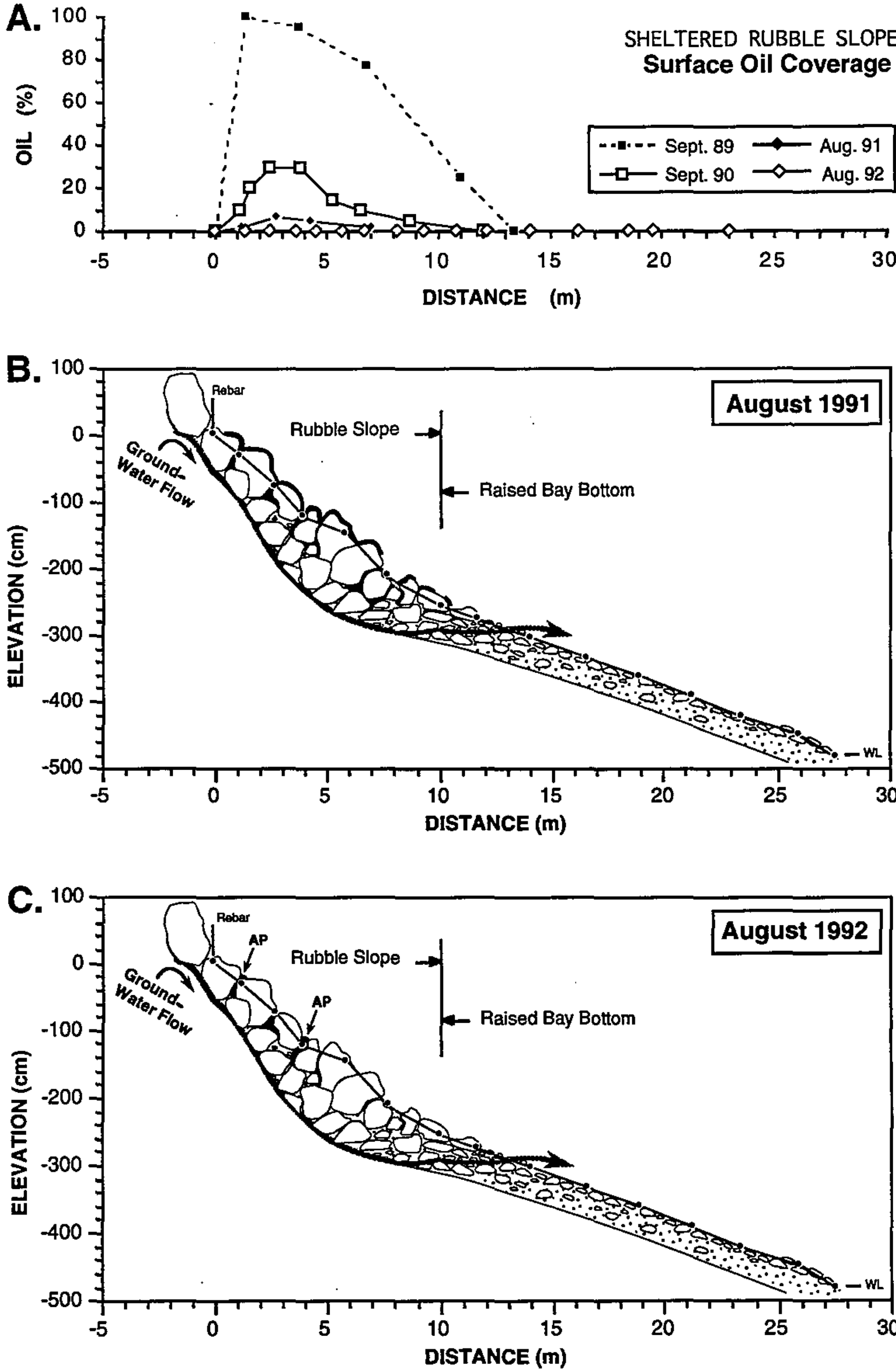
Figure 6-3. Schematic model of the behavior and persistence of oil from the initial stranding to the end of 1992 on sheltered rocky coasts which have a very thin sediment veneer.

weathered into semi-hard black pavements. These oil deposits are likely to persist for very long periods, up to decades.

The oil distribution and persistence schematic for rocky rubble slopes is shown in Figure 6-4, and it has many contrasts with the sheltered rocky coasts. The most important differences are the greater depth to the bedrock surface and the higher permeability of the sediment veneer. The rubble slopes are formed by the passive accumulation of rubble from the upland, and there is little sorting or reworking of the rubble. Thus, it is thicker than the veneer on bedrock slopes, and the permeability can be very high, but it is variable. The spaces between the large rubble are filled with sediment—mostly pebbles, granules, and sand—but are loosely packed in some areas. If there is groundwater seepage from the upland, it generally flows on top of the bedrock and between the rubble.

Surface oil distribution and behavior were the same as for all rocky shores, with coverage on the upper half of the coastline and steady decreases over time to only traces after two years. Small incipient pavements occurred, mostly at the base of the surface rubble. Subsurface oil, however, had a very different behavior. The depth of oil penetration was highly variable, ranging from negligible to over 50 cm, with the deeper penetration along the rubble/matrix contact. The degree of oiling was much lower, since the porosity of the finer-grained matrix was low and the water content could be high. The subsurface oil concentrations changed slowly over time. Also, the subsurface oil in these habitats had weathered slowly, which is surprising. We would have predicted that tidal and groundwater flushing should be much more effective in oil removal and degradation. Perhaps the pattern of water flow changed in the areas where oil filled the crevices, though it does not seem likely. Whatever the mechanism, the rubble slopes have shown some of the slowest rates of oil removal and probably benefited the greatest from early cleanup efforts.

Figure 6-4. (Facing Page) Schematic model of the behavior and persistence of oil from the initial stranding to the end of 1992 on sheltered, rocky rubble slopes which have a relatively thick veneer of sediments that have some permeability.


A.
SHELTERED RUBBLE SLOPES
Surface Oil Coverage
OIL (%)
Sept. 89
Aug. 91
Sept. 90
Aug. 92
DISTANCE (m)
B.
August 1991
Rebar
Rubble Slope
Raised Bay Bottom
Ground-Water Flow
ELEVATION (cm)
WL
DISTANCE (m)
C.
August 1992
Rebar
AP
AP
Rubble Slope
Raised Bay Bottom
Ground-Water Flow
ELEVATION (cm)
WL
DISTANCE (m)

APPENDIX

Concentrations of Targeted Polynuclear Aromatic Hydrocarbons in Samples from Selected Stations August 1992

SAMPLE NAME:	Reference Oil	N-1, Tr. B (40-55 cm)	N-1, storm berm	N-3, Tr. A (35-42 cm)
COMPOUND	ng/mg* (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPHTHALENE,a, f	1,209.00	0.00	0.00	0.00
C-1 NAPHTHALENE	2,582.00	0.18	0.00	0.02
C-2 NAPHTHALENE	3,072.00	7.32	0.00	0.27
C-3 NAPHTHALENE	1,830.00	13.10	0.00	0.85
C-4 NAPHTHALENE	81.00	11.56	0.00	1.02
FLUORENE, a, f	112.00	0.00	0.00	0.00
C-1 FLUORENE	211.00	2.12	0.00	0.12
C-2 FLUORENE	233.00	4.77	0.03	0.30
C-3 FLUORENE	148.00	3.39	0.08	0.37
DIBENZOTHIO., b, f	274.00	0.00	0.00	0.00
C-1 DIBENZOTHIO.	411.00	4.92	0.00	0.23
C-2 DIBENZOTHIO.	457.00	9.16	0.14	0.77
C-3 DIBENZOTHIO.	232.00	6.40	0.27	0.77
PHENANTHRENE, b, f	455.00	1.82	0.00	0.06
C-1 PHENANTHRENE	828.00	7.99	0.05	0.45
C-2 PHENANTHRENE	650.00	11.49	0.17	0.84
C-3 PHENANTHRENE	331.00	8.55	0.35	0.84
ANTHRACENE, b, f	0.00	0.00	0.00	0.00
NAPHTHOBENZTHIO.,b	3.74	0.41	0.01	0.09
C-1 NBTP	35.00	1.18	0.05	0.15
C-2 NBTP	45.00	1.48	0.16	0.34
C-3 NBTP	30.76	1.08	0.17	0.36
FLUORANTHENE, b, f	0.00	0.00	0.00	0.00
PYRENE, b, f	24.00	0.47	0.00	0.09
C-1 PYRENE	77.00	1.77	0.27	0.41
C-2 PYRENE	121.00	2.73	0.48	0.81
BENZO(a)ANT.	0.00	0.00	0.00	0.00
CHRYSENE, c, g	77.00	1.66	0.41	0.55
C-1 CHRYSENE	115.00	2.79	0.44	0.77
C-2 CHRYSENE	105.00	2.60	0.44	0.77
BENZO(b)FLU.*, d, g	3.22	0.23	0.00	0.00
BENZO(e)PYRENE, d, g	12.00	0.31	0.00	0.16
BENZO(a)PYRENE, d, g	0.00	0.00	0.00	0.00
PERYLENE, d, g	0.00	0.00	0.00	0.00
IND.(1,2,3-cd)PYR., d, g	0.00	0.00	0.00	0.00
DIBENZ.(a,h)ANT., d, g	0.00	0.00	0.00	0.00
BENZ.(g,h,i)PER., d,g	0.00	0.00	0.00	0.00
TOTAL TARGET AH:	13,774.00	109.49	3.51	11.41
HOPANE**	NA	NA	NA	NA
S.S. d-10 ACE., e	NA	NA	NA	NA
S.S. d-10 PHEN., f	NA	NA	NA	NA
S.S. d-14 TERP., g	NA	NA	NA	NA

* ng/mg = nanogram per milligram

SAMPLE NAME: COMPOUND	N-3, Tr. B (15-25 cm) ng/mg (wet)	N-7, Tr. A (25-40 cm) ng/mg (wet)	N-7, Tr. B (35-45 cm) ng/mg (wet)	N-7, Tr. C (35-45 cm) ng/mg (wet)
NAPHTHALENE,a, f	0.00	0.00	0.00	0.00
C-1 NAPHTHALENE	0.03	0.00	0.03	0.02
C-2 NAPHTHALENE	0.24	0.02	0.09	0.44
C-3 NAPHTHALENE	1.19	0.17	0.45	1.90
C-4 NAPHTHALENE	3.19	3.12	4.01	3.35
FLUORENE, a, f	0.00	0.00	0.00	0.00
C-1 FLUORENE	0.18	0.10	0.26	0.28
C-2 FLUORENE	1.10	0.84	1.14	0.86
C-3 FLUORENE	1.83	1.64	1.98	1.50
DIBENZOTHIO., b, f	0.02	0.00	0.00	0.04
C-1 DIBENZOTHIO.	0.36	0.22	0.22	0.57
C-2 DIBENZOTHIO.	2.36	2.53	3.37	3.04
C-3 DIBENZOTHIO.	2.32	3.60	4.36	3.83
PHENANTHRENE, b, f	0.05	0.00	0.05	0.14
C-1 PHENANTHRENE	0.53	0.24	0.31	0.88
C-2 PHENANTHRENE	1.81	1.80	2.11	2.65
C-3 PHENANTHRENE	2.65	4.29	4.65	4.05
ANTHRACENE, b, f	0.02	0.00	0.00	0.06
NAPHTHOBENZTHIO.,b	0.10	0.18	0.20	0.02
C-1 NBTP	0.41	0.66	0.77	0.74
C-2 NBTP	0.64	0.97	1.09	1.08
C-3 NBTP	0.59	0.68	0.74	0.79
FLUORANTHENE, b, f	0.00	0.11	0.11	0.00
PYRENE, b, f	0.17	0.40	0.54	0.38
C-1 PYRENE	0.81	1.15	1.50	1.26
C-2 PYRENE	1.30	2.28	2.50	2.20
BENZO(a)ANT.	0.00	0.00	0.00	0.00
CHRYSENE, c, g	0.72	1.31	1.38	1.20
C-1 CHRYSENE	1.10	2.13	2.27	2.10
C-2 CHRYSENE	1.21	2.04	2.37	2.15
BENZO(b)FLU.*, d, g	0.00	0.00	0.00	0.14
BENZO(e)PYRENE, d, g	0.18	0.00	0.00	0.29
BENZO(a)PYRENE, d, g	0.00	0.00	0.00	0.00
PERYLENE, d, g	0.00	0.00	0.00	0.00
IND.(1,2,3-cd)PYR., d, g	0.00	0.00	0.00	0.00
DIBENZ.(a,h)ANT., d, g	0.00	0.00	0.00	0.00
BENZ.(g,h,i)PER., d,g	0.00	0.00	0.00	0.00
TOTAL TARGET AH:	25.10	30.49	36.52	35.96
HOPANE**	NA	NA	NA	NA
S.S. d-10 ACE., e	NA	NA	NA	NA
S.S. d-10 PHEN., f	NA	NA	NA	NA
S.S. d-14 TERP., g	NA	NA	NA	NA

SAMPLE NAME:	N-9, Tr. F (0-10 cm)	N-9, Tr. F (0-10 cm) Duplicate	N-10, Tr. A (30-40 cm)	N-10, Tr. A (25-30 cm)
COMPOUND	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPHTHALENE,a, f	0.00	0.00	0.00	0.00
C-1 NAPHTHALENE	0.00	0.00	0.00	0.00
C-2 NAPHTHALENE	0.00	0.00	0.27	0.00
C-3 NAPHTHALENE	0.00	0.00	0.96	0.04
C-4 NAPHTHALENE	0.01	0.00	0.90	0.03
FLUORENE, a, f	0.00	0.00	0.00	0.00
C-1 FLUORENE	0.00	0.00	0.13	0.05
C-2 FLUORENE	0.00	0.00	0.26	0.20
C-3 FLUORENE	0.01	0.00	0.19	0.23
DIBENZOTHIO., b, f	0.00	0.00	0.00	0.00
C-1 DIBENZOTHIO.	0.00	0.00	0.27	0.01
C-2 DIBENZOTHIO.	0.01	0.01	0.52	0.28
C-3 DIBENZOTHIO.	0.01	0.01	0.33	0.37
PHENANTHRENE, b, f	0.00	0.00	0.00	0.01
C-1 PHENANTHRENE	0.00	0.00	0.45	0.07
C-2 PHENANTHRENE	0.01	0.01	0.64	0.24
C-3 PHENANTHRENE	0.01	0.02	0.50	0.51
ANTHRACENE, b, f	0.00	0.00	0.00	0.01
NAPHTHOBENZTHIO.,b	0.00	0.00	0.02	0.02
C-1 NBTP	0.00	0.00	0.05	0.15
C-2 NBTP	0.00	0.00	0.09	0.47
C-3 NBTP	0.00	0.00	0.05	0.70
FLUORANTHENE, b, f	0.00	0.00	0.00	0.01
PYRENE, b, f	0.00	0.00	0.00	0.04
C-1 PYRENE	0.00	0.00	0.10	0.25
C-2 PYRENE	0.00	0.00	0.22	0.47
BENZO(a)ANT.	0.00	0.00	0.00	0.00
CHRYSENE, c, g	0.00	0.01	0.00	0.41
C-1 CHRYSENE	0.01	0.01	0.21	0.51
C-2 CHRYSENE	0.00	0.01	0.22	0.54
BENZO(b)FLU.*, d, g	0.00	0.00	0.00	0.07
BENZO(e)PYRENE, d, g	0.00	0.00	0.00	0.11
BENZO(a)PYRENE, d, g	0.00	0.00	0.00	0.00
PERYLENE, d, g	0.00	0.00	0.00	0.00
IND.(1,2,3-cd)PYR., d, g	0.00	0.00	0.00	0.00
DIBENZ.(a,h)ANT., d, g	0.00	0.00	0.00	0.00
BENZ.(g,h,i)PER., d,g	0.00	0.00	0.00	0.05
TOTAL TARGET AH:	0.09	0.10	6.39	5.86
HOPANE**	NA	NA	NA	NA
S.S. d-10 ACE., e	NA	NA	NA	NA
S.S. d-10 PHEN., f	NA	NA	NA	NA
S.S. d-14 TERP., g	NA	NA	NA	NA

SAMPLE NAME: COMPOUND	N-11, Tr. A (0-5 cm) ng/mg (wet)	N-13 Tr. A (15-25 cm) ng/mg (wet)	N-13, Tr. B (15-25 cm) ng/mg (wet)	N-13, Tr. B (15-25 cm) Duplicate ng/mg (wet)
NAPHTHALENE,a, f	0.00	0.00	0.00	0.00
C-1 NAPHTHALENE	0.00	0.00	0.05	0.00
C-2 NAPHTHALENE	0.00	0.09	0.11	0.00
C-3 NAPHTHALENE	0.22	0.78	0.40	0.00
C-4 NAPHTHALENE	2.85	1.90	0.68	0.01
FLUORENE, a, f	0.00	0.00	0.00	0.00
C-1 FLUORENE	0.05	0.07	0.09	0.00
C-2 FLUORENE	1.01	0.53	0.28	0.00
C-3 FLUORENE	1.35	0.66	0.30	0.00
DIBENZOTHIO., b, f	0.00	0.00	0.00	0.00
C-1 DIBENZOTHIO.	0.00	0.24	0.18	0.00
C-2 DIBENZOTHIO.	0.24	1.27	0.75	0.01
C-3 DIBENZOTHIO.	2.82	1.27	0.82	0.01
PHENANTHRENE, b, f	0.00	0.00	0.00	0.00
C-1 PHENANTHRENE	0.16	0.41	0.33	0.00
C-2 PHENANTHRENE	2.23	1.23	0.90	0.01
C-3 PHENANTHRENE	3.35	1.73	1.23	0.01
ANTHRACENE, b, f	0.00	0.00	0.00	0.00
NAPHTHOBENZTHIO.,b	0.02	0.75	0.05	0.00
C-1 NBTP	0.42	0.27	0.18	0.00
C-2 NBTP	0.64	0.49	0.43	0.00
C-3 NBTP	0.45	0.48	0.33	0.00
FLUORANTHENE, b, f	0.00	0.00	0.00	0.00
PYRENE, b, f	0.27	0.08	0.00	0.00
C-1 PYRENE	1.09	0.43	0.20	0.00
C-2 PYRENE	1.85	0.64	0.42	0.00
BENZO(a)ANT.	0.00	0.00	0.00	0.00
CHRYSENE, c, g	1.10	0.41	0.20	0.00
C-1 CHRYSENE	1.74	0.61	0.47	0.01
C-2 CHRYSENE	1.47	0.67	0.50	0.00
BENZO(b)FLU.*, d, g	0.00	0.05	0.07	0.00
BENZO(e)PYRENE, d, g	0.00	0.11	0.09	0.00
BENZO(a)PYRENE, d, g	0.00	0.00	0.00	0.00
PERYLENE, d, g	0.00	0.00	0.00	0.00
IND.(1,2,3-cd)PYR., d, g	0.00	0.00	0.00	0.00
DIBENZ.(a,h)ANT., d, g	0.00	0.00	0.00	0.00
BENZ.(g,h,i)PER., d,g	0.00	0.00	0.00	0.00
TOTAL TARGET AH:	23.33	15.17	9.07	0.10
HOPANE**	NA	NA	NA	NA
S.S. d-10 ACE., e	NA	NA	NA	NA
S.S. d-10 PHEN., f	NA	NA	NA	NA
S.S. d-14 TERP., g	NA	NA	NA	NA

SAMPLE NAME: COMPOUND	N-15, Tr. C (10-15 cm) ng/mg (wet)	N-15, Tr. C (10-15 cm) Duplicate ng/mg (wet)	N-17, Tr. A (5-15 cm) ng/mg (wet)	Elrington Is. Tr E (10-15 cm) ng/mg (wet)	Elrington Is Tr. E Duplicate ng/mg (wet)
NAPHTHALENE,a, f	0.00	0.00	0.00	0.00	0.00
C-1 NAPHTHALENE	0.01	0.00	0.01	0.01	0.01
C-2 NAPHTHALENE	0.01	0.20	0.14	1.30	1.75
C-3 NAPHTHALENE	0.03	0.07	0.70	5.19	8.73
C-4 NAPHTHALENE	0.20	0.09	0.96	5.62	10.07
FLUORENE, a, f	0.01	0.00	0.00	0.00	0.00
C-1 FLUORENE	0.02	0.01	0.12	1.10	1.66
C-2 FLUORENE	0.17	0.04	0.52	2.04	3.60
C-3 FLUORENE	0.30	0.04	0.45	2.46	4.06
DIBENZOTHIO., b, f	0.00	0.00	0.03	0.12	0.15
C-1 DIBENZOTHIO.	0.04	0.04	0.24	1.66	2.53
C-2 DIBENZOTHIO.	0.46	0.11	0.86	3.73	6.20
C-3 DIBENZOTHIO.	0.68	0.10	0.80	3.38	5.37
PHENANTHRENE, b, f	0.07	0.01	0.05	0.36	0.44
C-1 PHENANTHRENE	0.14	0.07	0.41	2.86	3.69
C-2 PHENANTHRENE	0.74	0.14	0.98	4.73	7.20
C-3 PHENANTHRENE	1.11	0.15	1.15	3.75	5.22
ANTHRACENE, b, f	0.00	0.00	0.00	0.00	0.00
NAPHTHOBENZTHIO. ,b	0.02	0.01	0.06	0.18	0.28
C-1 NBTP	0.02	0.02	0.19	0.63	0.82
C-2 NBTP	0.46	0.05	0.39	0.86	1.20
C-3 NBTP	0.49	0.06	0.47	0.75	1.07
FLUORANTHENE, b, f	0.02	0.00	0.01	0.02	0.03
PYRENE, b, f	0.07	0.01	0.04	0.15	0.29
C-1 PYRENE	0.40	0.05	0.19	0.56	1.05
C-2 PYRENE	0.72	0.13	0.34	0.86	1.46
BENZO(a)ANT.	0.01	0.00	0.02	0.07	0.06
CHRYSENE, c, g	0.69	0.07	0.25	0.64	1.21
C-1 CHRYSENE	0.73	0.11	0.35	0.91	1.64
C-2 CHRYSENE	0.73	0.11	0.39	0.95	1.80
BENZO(b)FLU.*, d, g	0.09	0.01	0.05	0.16	0.17
BENZO(e)PYRENE, d, g	0.22	0.03	0.07	0.12	0.21
BENZO(a)PYRENE, d, g	0.00	0.00	0.00	0.00	0.00
PERYLENE, d, g	0.00	0.00	0.00	0.00	0.00
IND.(1,2,3-cd)PYR., d, g	0.00	0.00	0.00	0.00	0.00
DIBENZ.(a,h)ANT., d, g	0.00	0.00	0.00	0.00	0.00
BENZ.(g,h,i)PER., d,g	0.10	0.00	0.04	0.00	0.00
TOTAL TARGET AH:	8.74	1.55	10.27	45.19	71.97
HOPANE**	NA	NA	NA	NA	NA
S.S. d-10 ACE., e	NA	NA	NA	NA	NA
S.S. d-10 PHEN., f	NA	NA	NA	NA	NA
S.S. d-14 TERP., g	NA	NA	NA	NA	NA

GLOSSARY

AP	asphalt pavement
B	boulders
C	cobble
cm	centimeter
CT	coat
CV	cover
G	granules
GC/MS	gas chromatography/mass spectroscopy
HOR	heavy oil residue
km	kilometer
LOR	light oil residue
LSU	Louisiana State University
m	meter
mg/kg	milligram per kilogram
mm	millimeter
MOR	medium oil residue
ng/kg	nanogram per milligram
NOAA	National Oceanic and Atmospheric Administration
OF	oil film
P	pebbles
PAH	polynuclear aromatic hydrocarbons
RPI	Research Planning Inc.
S	sand
ST	stain
TPH	total petroleum hydrocarbons
TR	trench

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