NOAA Technical Memorandum NOS ORCA 91

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

Volume II 1994 Geomorphological Monitoring Survey, July 1994

Seattle, Washington
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National Ocean Service

Office of Ocean Resources Conservation and Assessment
National Ocean Service
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Evaluation of the Condition of Prince William Sound Shorelines Following the Exxon Valdez Oil Spill and Subsequent Shoreline Treatment

Volume II 1994 Geomorphological Monitoring Survey

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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 evolved 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.

Three of the original stations, N-5, N-6, and N-13 (Figure 1-1), were at locations 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 have been repeated up to thirteen times over the period September 1989 to July 1994. It has been two years since the last survey. 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 shoreline types were heavily oiled during the spill.

Results based on the surveys conducted through August 1992 have been presented elsewhere (Michel et al. 1990, Michel and Hayes 1991, Michel et al. 1991, and Michel and Hayes 1993a, 1993b, and 1993c). This report synthesizes the data collected during the survey of July 1994 with the earlier results.

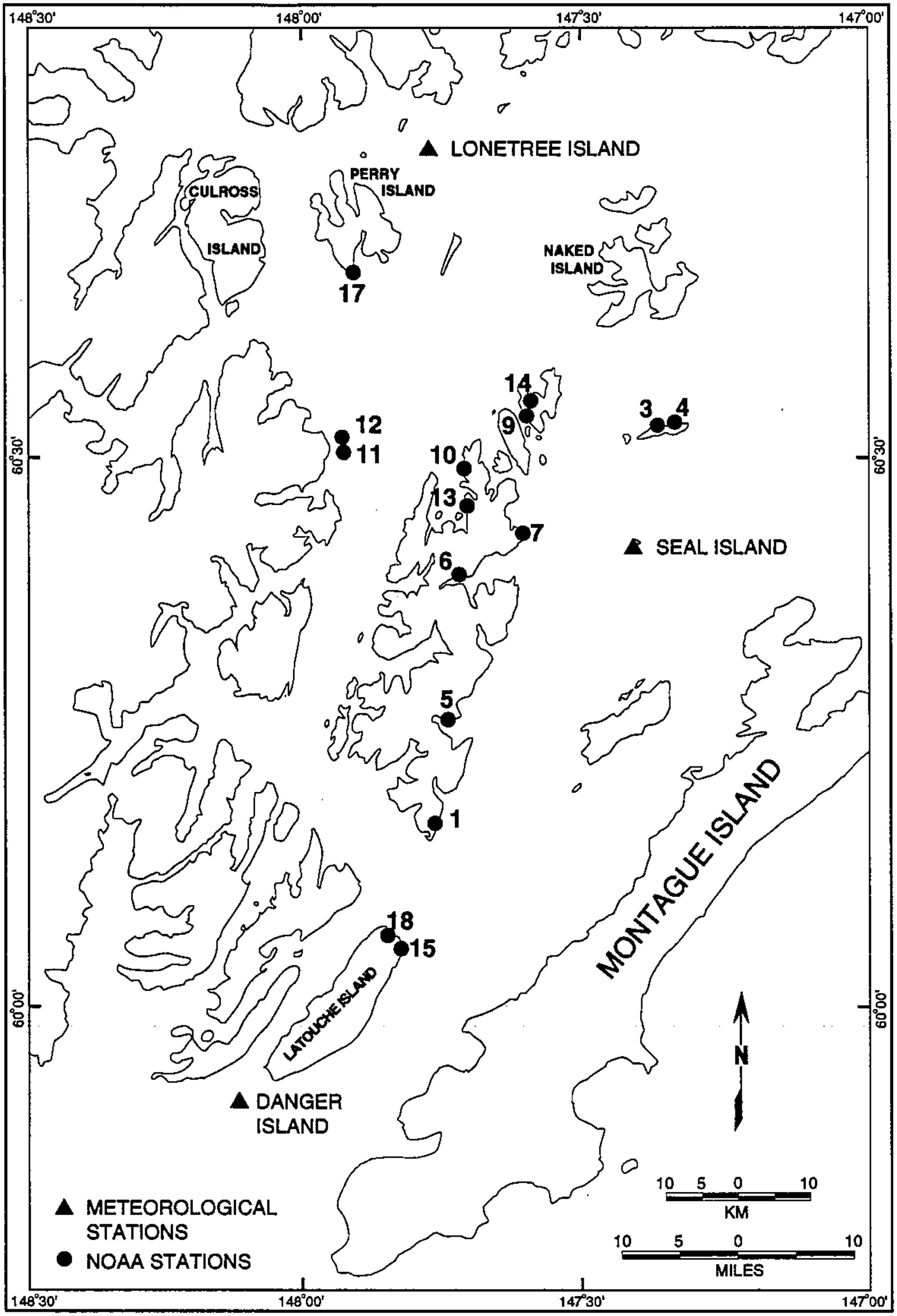


Figure 1-1. Location of permanent stations (dots) surveyed as part of NOAA's geomorphology/chemistry monitoring program during the July 1994 survey, and NOAA meteorology stations (triangles).

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 13 times to date during the project, the first time in September 1989 and the last in July 1994. 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 survey interval. The station was photographed and sketched in detail, highlighting the distribution of oil, if present, and the effects of cleanup. Trenches were dug at intervals along the profile to determine the depth of oil penetration. Each trench was described and photographed in detail.

Samples were collected of both surface and subsurface oil contamination, usually oiled sediments. Surface oiled sediment samples, the top two centimeters (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. Twenty-four (24) samples were collected during the July 1994 survey.

To date, over 820 samples have been analyzed for total petroleum hydrocarbons (TPH). Over 120 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 at Louisiana State University. TPH was determined gravimetrically after solvent extraction with freon (Standard Method 503). All sample extracts were also analyzed by GC/MS, targeting 37 PAHs known to characterize petroleum hydrocarbons. The results for individual PAHs are listed in Appendix 1. Table 2-2 lists the samples collected, the visual descriptions of oiling as recorded in the field, and the TPH and total targeted PAH results in milligrams of oil per kilogram of sediment (mg/kg), dry weight.

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

	1989				1990						1991		1992	1994
Station Number	16-20 Sept.	17-23 Oct.	3-9 Nov.	3-8 Dec.	1-6 Jan.	30 Jan.- 3 Feb.	28 Feb.- 5 Mar.	23-31 May	22-23 June	1-8 Sept.	19-25 Jan.	25-29 Aug.	10-16 Aug.	21-26 July
N-1	X	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	X
N-4	X	X		X	X	X	X	X		X	X	X		X
N-5	X	X		X	X	X		X		X		X		X
N-6	X	X			X			X		X		X	X	X
N-7	X	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	X
N-10	X	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	X
N-12	X	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	X
N-14	X	X		X		X		X		X	X		X	X
N-15	X	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	X
N-18	X	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. Results of chemical analyses of sediment samples collected during the July 1994 survey.

Station No.	Zone[1]	Depth (cm)	Visual Oil[2] Description	TPH (mg/kg)	Total PAH (mg/kg)
Point Helen					
N-1	Tr. B, Upper platform	30-50	OF	1,000	0.6
	Tr. B, Upper platform	66	HOR	18,000	360
	Tr. C, Lower platform	60-65	HOR	7,900	180
Smith Island					
N-3	Tr. A, Upper platform	25-35	HOR	16,000	300
	Tr. B, Upper platform	15-25	HOR	17,000	250
Snug Harbor					
N-5	Tr. A, Raised bay bottom	0-3	AP	32,000	330
Bay of Isles					
N-6	Tr. A, Upper rocky	0-5	AP	27,000	150
	Tr. B, Upper rocky	0-5	AP	36,000	230
NE Knight Island					
N-7	Tr. A, Upper platform	36-42	LOR	2,900	2.2
	Tr. A, Upper platform	35-45	LOR	600	1.6
	Tr. B, Upper platform	35-42	LOR	3,300	3.8
	Tr. C, Upper platform	35-45	MOR	4,500	16
	Tr. C, Upper platform	55-60	HOR	7,700	17
Block Island					
N-9	Tr. B, Tidal flat	2-10	OF	80	0.2
Herring Bay					
N-10	Low-tide zone trench	35-52	LOR	470	13
	High-tide trench	45-60	LOR	-	-
	Upper rockface	0	CT	-	-
Crafton Island					
N-11	Tr. A, Beachface	0-5	MOR	2,100	32
	Tr. A, Beachface	0-10	MOR	800	5.8
Herring Bay					
N-13	Tr. A, Upper rubble	15-25	MOR	3,800	45
	Tr. B, Upper rubble	15-25	MOR	4,700	120
Latouche Island					
N-15	Tr. B, Upper platform	35-41	OF	760	0.2
Perry Island					
N-17	Tr. A, Central ramp	35-45	No Oil	50	0.2
	Upper rockface	0-2	AP	7,300	9.5

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

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

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 millimeter (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. For the July 1994 survey, five sediment samples were described as HOR, and the actual TPH concentrations ranged from 7,700-17,900 mg/kg.

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

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

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

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

class		size range
granule	—	2-4 mm
pebble	—	4-64 mm
cobble	—	64-256 mm
boulder	—	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 JULY 1994 SURVEY

INTRODUCTION

The July 1994 survey was conducted to observe the physical persistence and chemical weathering of oil residues along the various shoreline types in Prince William Sound after five years. Two years had passed since the last survey, which was conducted in August 1992.

The results of the July 1994 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 three 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 1993a) and the August 1992 survey (Michel and Hayes 1993c).

COBBLE/BOULDER PLATFORMS WITH BERMS

Introduction

The shorelines in this class are the most exposed, as well as the coarsest-grained, beaches occurring in Prince William Sound. Six of the stations surveyed during the July 1994 field study were classified in this category, cobble/boulder platforms with berms. A more general term for these beaches would be relatively exposed gravel beaches. However, their morphology is somewhat unique, primarily because all of the sites were uplifted during the Good Friday earthquake of 1964, and they do not appear to have yet achieved equilibrium with respect to beach-forming processes. The typical morphology of these beaches is illustrated by the topographic profile in Figure 3-1A. The most landward part of the beach usually contains an elevated storm berm which has lower-level spring-tide and neap-tide berms superimposed on its relatively steep seaward side. On gravel beaches, the coarser gravel fractions are moved landward during storms, forming the peaked mound of coarse gravel called the storm berm. This pattern is in contrast to sand beaches, where the sediment is moved offshore during storms. All of the gravel beaches in this class are underlain by what appear to be uplifted wave-cut rock platforms, which are usually steeper on the landward half (upper platform; Figure 3-1A). As discussed earlier (Michel and Hayes 1991, 1993a, and 1993c), the gravel that overlies the bedrock platform has a veneer, or armor, of well-sorted cobbles and boulders as a result of the finer clasts having been winnowed away by storm-wave-generated currents. The sediment under the armor is considerably finer-grained than the armor itself, even containing sand and granules with depth. When these beaches were covered with oil during the spill, some of the oil penetrated through the overlying armor and into the protected finer-grained sediments below. The subsurface oil thus secured under the surface armor of coarse gravel was one of the most difficult issues dealt with during the spill cleanup. One of the primary goals of this survey was to determine the quantity and chemical makeup of any oil remaining under the armor after five years of exposure to natural processes of weathering and erosion.

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 (Figure 1.1). 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.

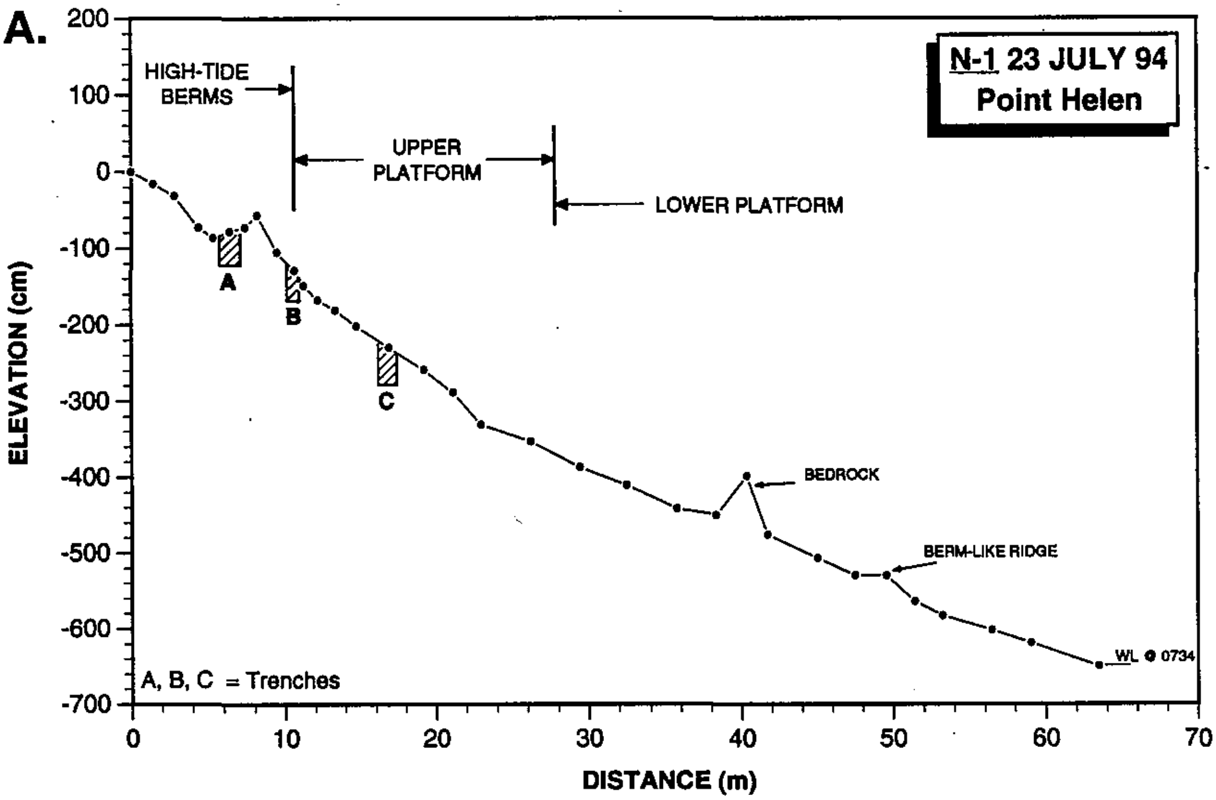
This station is one of the more exposed (to wave action) of our study sites, with an effective fetch of 15 to 20 km to the east and 45 to 50 km to the north-northeast. Wind data collected by NOAA at Lone Tree, Seal, and Danger Islands in Prince William Sound (Figure 1.1) for the storm season of 1989/1990 show that storm winds in the Sound blow overwhelmingly out of the north and northeast (discussed by Michel and Hayes 1991).

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

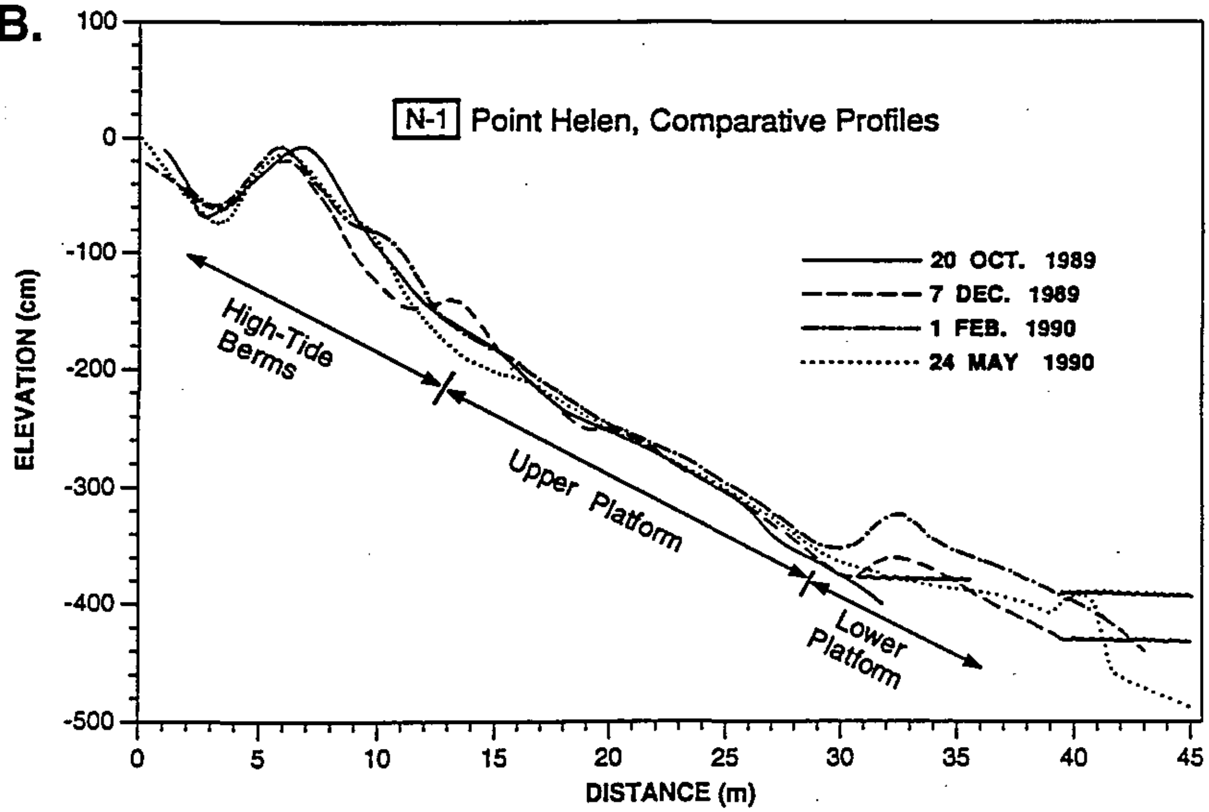
A. Topographic profile surveyed on 23 July 1994 showing morphological subdivisions and location of trenches dug on that date.

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 23 JULY 94
Point Helen
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
BEDROCK
BERM-LIKE RIDGE
WL @ 0734
A, B, C = Trenches
ELEVATION (cm)
DISTANCE (m)

B.


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

Morphology and sediments. The morphology of this station on 23 July 1994 is illustrated by the beach profile plot shown at a 5:1 vertical exaggeration in Figure 3-1A. The zone of the high-tide berms was modified significantly by a berm-relocation project carried out at the site in the summer of 1991 (discussed below). The present storm berm is somewhat smaller than the one that was destroyed by the berm-relocation project.

This beach exhibits a very strong north-to-south longshore sediment transport rate. 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) strikingly asymmetrical high-tide berms in the form of rhythmic topography moving south; and 3) clear grain-size trends from coarse to fine in a north to south direction.

The plots of sequential beach profile surveys shown in Figure 3-1B clearly illustrate the relatively large size of the original storm berm; the short-term changes on the offshore face of the storm berm, caused primarily by the migration of rhythmically spaced neap- and spring-tide berms; and the frequent occurrence of migrating gravel swash bars on the lower platform. The field sketch for the 1994 survey given in Figure 3-2C illustrates the presence of both high-tide rhythmic topography and lower intertidal gravel swash bars at the time of that survey.

As shown by the sediment distribution plots in Figure 3-3, sediment grain size increases in an offshore direction, with pebbles being most common in the high-tide berm area and boulders being most common on the lower platform. Examination of over 30 trenches dug at this site show that a surface armor has developed over the underlying sediments of the upper and lower platforms. In places, the mean clast size of the surface armor may be four times as great as that of the underlying sediment. Most of the gravel clasts are rounded as a result of abrasion during transport by wave-generated currents, another indication of the relatively high degree of wave energy at this site.

Storm berm relocation. As late as the summer of 1991, some zones of persistent subsurface oil remained under the extensive storm berm at Point Helen. Accordingly, a 2000 m-long segment of the storm berm was planed-off flat, exposing the oiled sediments. Although some of the most heavily oiled sediments were removed, much of the excavated sediment was pushed onto the upper platform (see Figures 3-2A and 3-4B). Station N-1 is located within the excavation zone.

In our report on the 1992 field survey (Michel and Hayes 1993c), the opinion was expressed that the complete removal of the storm berm at Point Helen has at least two inherent problems: 1) the length of time it may take the beach to recover to its original profile; and 2) aesthetic impairment of the beach for a long time. The nature of the recovery of the beach over the subsequent three years following the massive berm-relocation project is illustrated in Figures 3-2, 3-3, 3-4, and 3-5.

The sediments on the upper and lower platforms were considerably finer-grained than before the berm-relocation project (Figures 3-3A and B), as a result of the finer-grained high-tide berm sediments being pushed lower down into the intertidal zone. At the time of the 13 August 1992 survey, the area where the storm berm had been was still flat (Figures 3-2B, 3-4 C, and 3-5A). However, a 10 m-wide zone of high-tide berm material was located at the high-tide line and offshore of the flattened-out zone. This zone was the flank of a southerly migrating shoreline rhythm, as shown by the sketch in Figure 3-2B and the photograph in Figure 3-4C. A wide zone of pebbles extended well down the upper platform along the offshore flank of the shoreline rhythm (Figure 3-3C).

As the field sketch and ground photograph taken during the 23 July 1994 survey show (Figures 3-2C and 3-4D), the storm berm was beginning to recover three years after the relocation. However, as seen in the comparison beach profile plots in Figure 3-5, the storm berm was still considerably smaller than it was in 1990. The gravel that had been pushed onto the upper and lower platforms, as well as that deposited by the migrating shoreline rhythm (in 1992), had been mostly eroded by the time of the 1994 survey, and the platform region was near the same elevation as it was in 1990 (Figure 3-5B). The surface sediment distribution had also returned to near its original pattern (Figure 3-3A and D).

Therefore, three years after the berm-relocation project, the beach has not completely returned to its original morphological configuration. Also, the chaotic piling of logs and large boulders left behind the beach during the relocation has changed little (see photographs in Figure 3-4). However, the sediment distribution pattern and the armored surface of the upper platform has been restored to near its original character.

Surface oil. As shown in Table 3-1, station N-1 was the only gravel beach station to retain surface oil during the July 1994 survey. A reading of 5 percent cover and coat was recorded for the area of the flattened out storm berm. Beginning with the May 1990 survey, during which a maximum reading of 100 percent oiling was recorded, this station has always had the highest amount of surface oil of any of the exposed gravel beaches. The early high readings were the result of oily debris being pushed over the top of the storm berm during a mid-October 1989 storm. The high readings of 75 percent during the August 1991 survey and 50 percent during the August 1992 survey were the

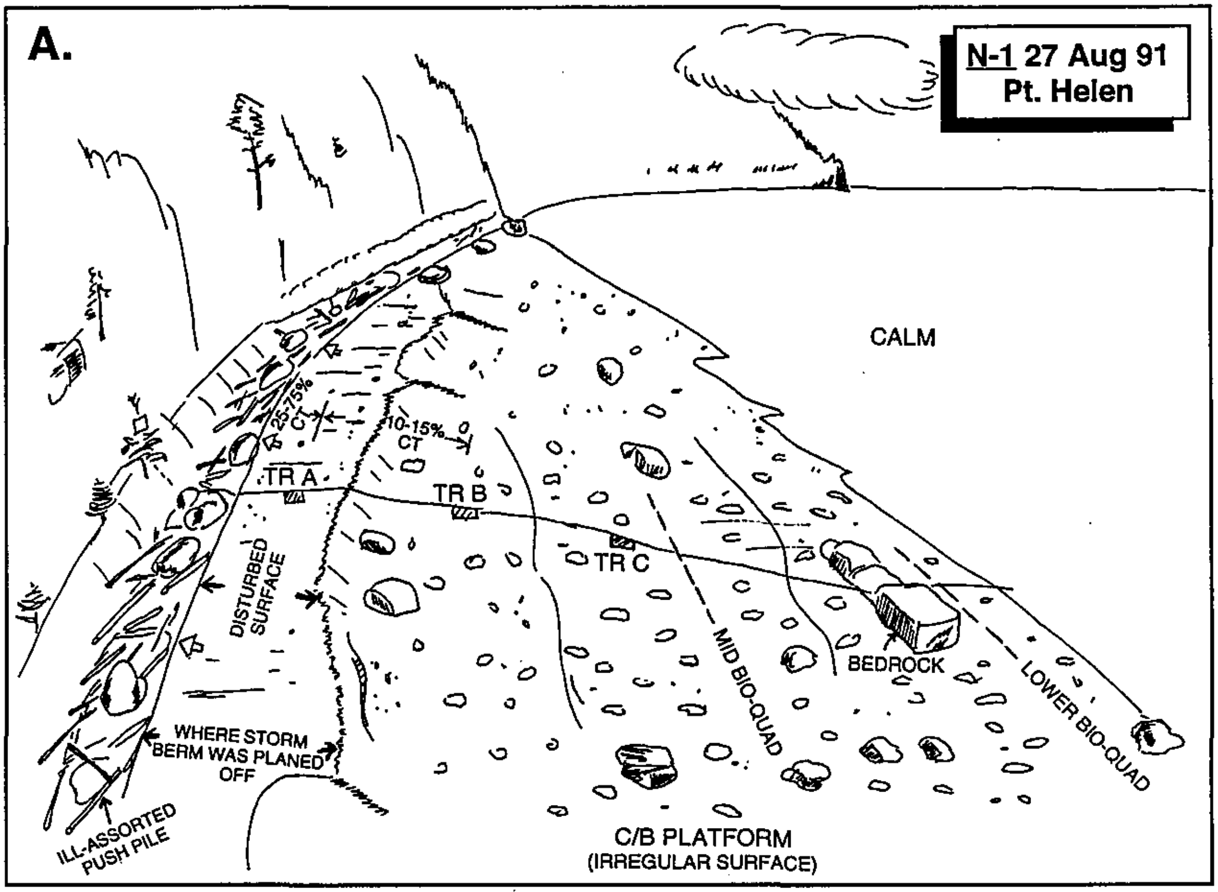
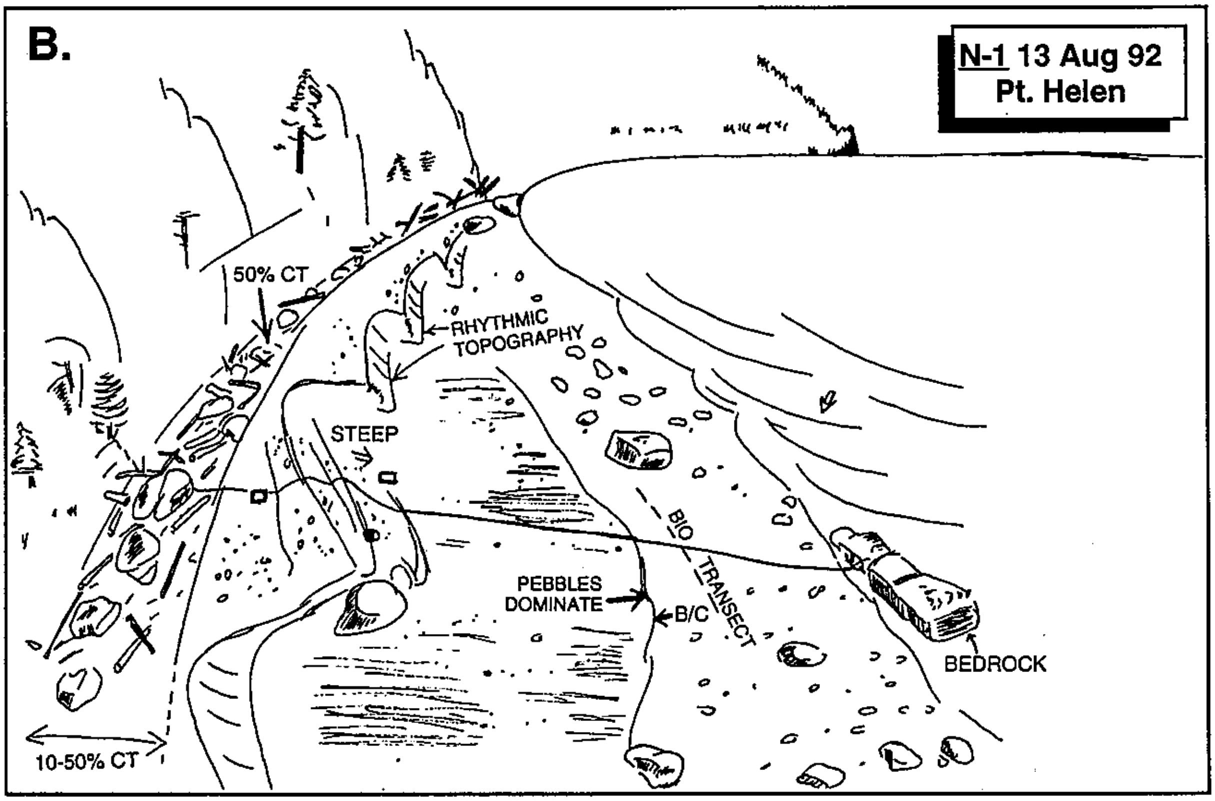
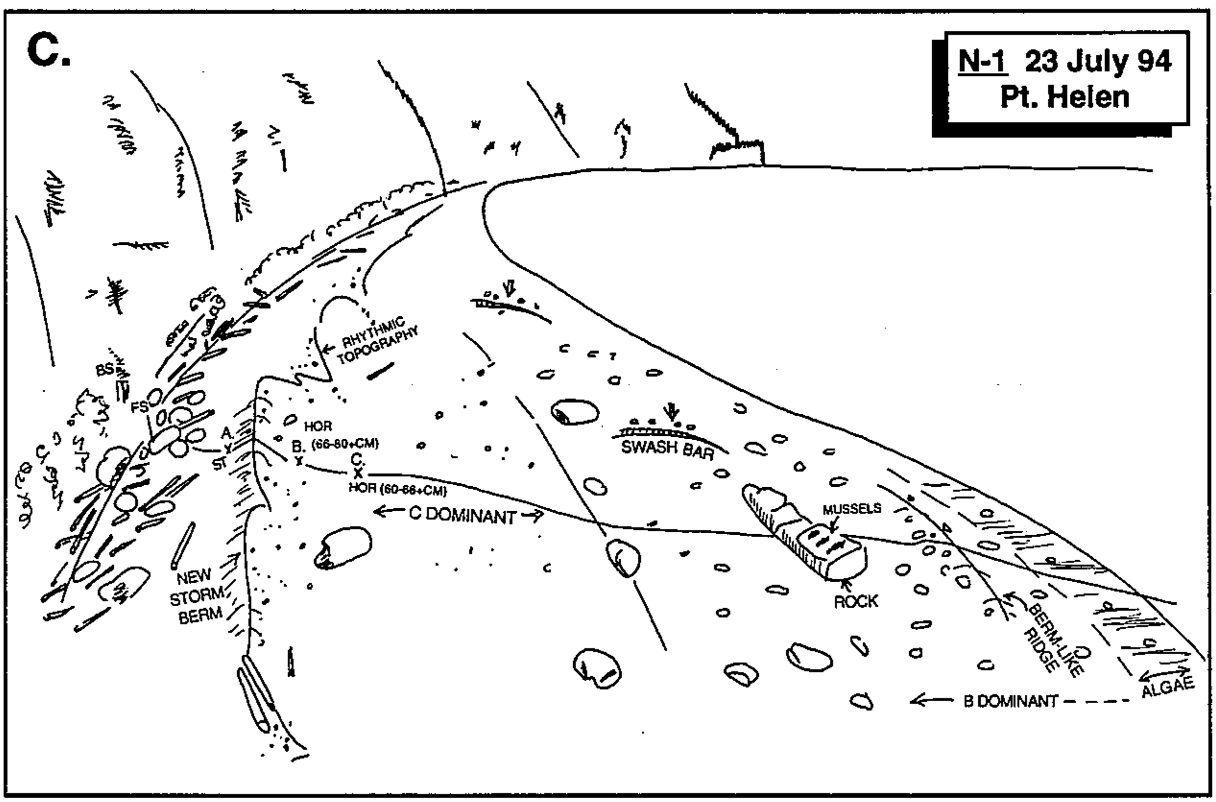


Figure 3-2. (Above and Facing Page) Field sketches of station N-1 (Point Helen). Compare with photographs in Figure 3-4.

- **A.** 27 August 1991. Note planed-off nature of the storm-berm area resulting from the berm-relocation project.
- **B.** 13 August 1992. Rhythmic topography had developed along high-tide line adjacent to the planed-off area.
- **C.** 23 July 1994. A new storm berm had finally begun to form. Note rhythmic topography at high-tide line and southerly migrating swash bars on the lower intertidal zone.


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


C.
N-1 23 July 94
Pt. Helen
RHYTHMIC
TOPOGRAPHY
BS
FS
A
ST
HOR
B. (66-80+CM)
C.
HOR (60-66+CM)
C DOMINANT
SWASH BAR
MUSSELS
ROCK
NEW
STORM
BERM
BERM-LIKE
RIDGE
B DOMINANT
ALGAE

result of exposure on the surface of previously subsurface oiled clasts as a result of the berm-relocation project.

Subsurface oil. Table 3-2 and Figure 3-6 illustrate the subsurface oiling observed in trenches dug along the profile at Point Helen since September 1989. Several conventions are used in these summaries which require explanation:

1) The trench data are grouped by geomorphological zone. Figure 3-1 shows the boundaries of the three zones at N-1. The exact location of trenches in each zone varied somewhat during each survey. When two different trenches were dug within the same zone, they are shown on the same line and separated by a slash.

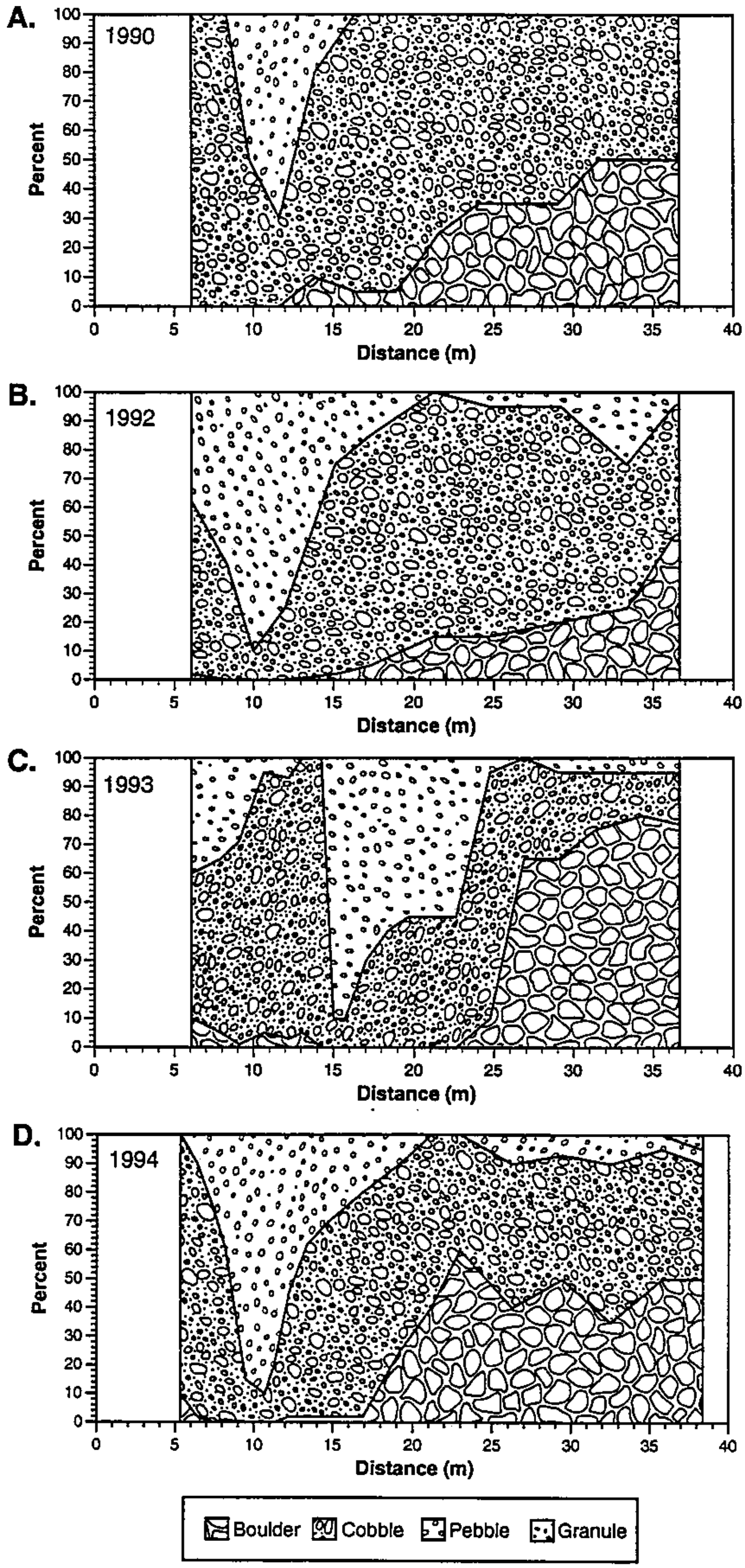
2) The depths are recorded as relative to the mean sediment surface, which does not include the parts of cobbles and boulders that protrude above the surface.

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 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. Because of the two-year interval between the 1992 and 1994 surveys, no lines are used to connect these data.

5) Only the oiled intervals are shown in each table. That is, if the top 25 cm in a trench were clean, with sediments containing light oil residue below, and clean sediments were not reached at the bottom of the trench at 40 cm, then the data for that month would be entered as 25-40+ (LOR).

Figure 3-3. **(Facing Page)** 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; (C) 13 August 1992; and (D) 23 July 1994. Note the changes in the middle two plots in response to the berm-relocation project, and the fact that the grain-size distribution in 1994 is quite similar to what it was before the berm relocation (compare A and D).


A.
1990
Percent
Distance (m)
B.
1992
C.
1993
D.
1994
Boulder
Cobble
Pebble
Granule

Reference to Figure 3-6A shows that by the end of the summer of 1989, oiling in the class MOR (TPH of 2,000-5,000 mg/kg) extended from the surface of the high-tide berm sediment to at least 48 cm depths. Other studies at Point Helen showed oil penetration to depths of 100 cm. By December 1989, the formation of new high-tide berms piled 15 cm of lightly oiled sediments on top of the heavily oiled zone (refer to Figure 3-1B). The lightly oiled surface sediments were reworked and cleaned by wave action until the sediments were clean down to depths of 25 cm by the time of the September 1990 survey. By the time of the January 1991 survey, most of the MOR subsurface oil had been removed naturally from the high-tide berm area, and only light oiling (<2,000 mg/kg) remained. After the major storm-berm relocation project in the summer of 1991, only oil stains on the cobbles and pebbles were observed. By 1994, the sediments remained lightly stained in the area behind the reforming storm berm, which was sheltering the sediments from reworking by wave action. Therefore, the berm relocation was effective in reducing the subsurface oil in the high-tide berms, but it should be noted that the levels of oil had already been significantly reduced by natural processes.

The subsurface oiling of the upper platform is demonstrated by the numbers in Table 3-2, the graphic plots in Figures 3-6 and 3-7, and the photographs in Figure 3-8. Subsurface oil was never observed to extend to the lower platform (see Figure 3-1 for geomorphic zones). After the summer of 1990, the top 20 cm of sediments on the upper platform had been cleaned of oil by natural processes. 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 from the top 30 cm. But the original subsurface oiled sediment layer

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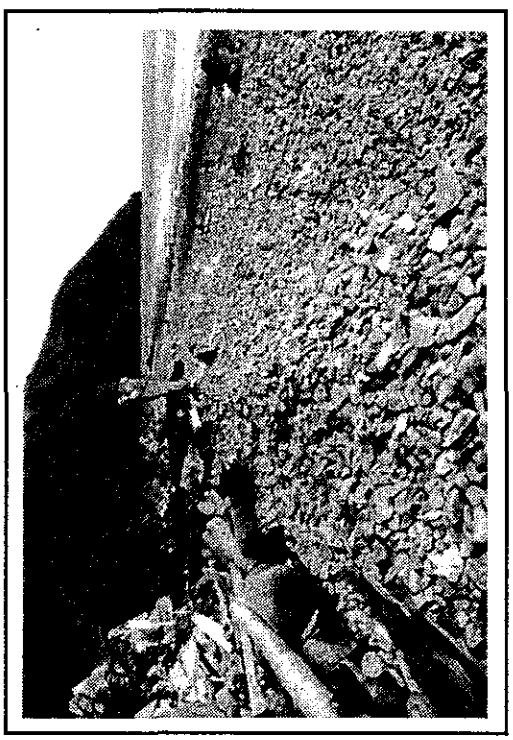
Figure 3-4. **(Facing Page)** Changes at station N-1 (Point Helen; Knight Island). All views look north.

A. 20 October 1989. Person is standing on crest of storm berm which had been recently activated by storm-generated waves. 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 3-2.

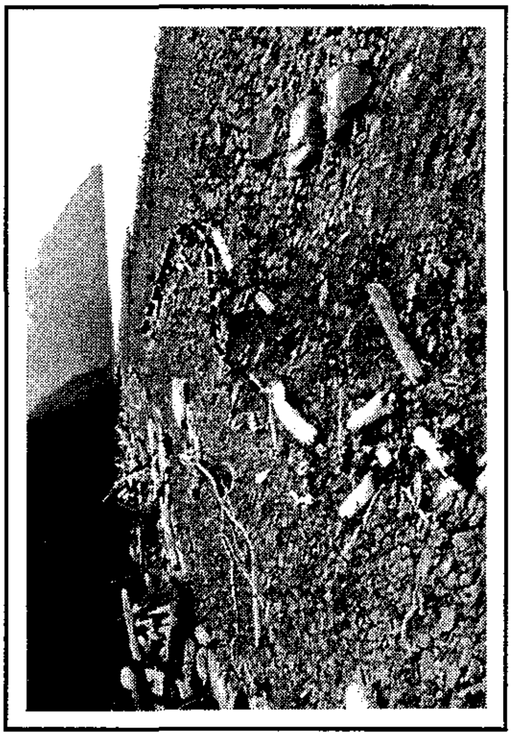
C. 13 August 1992. The new high-tide berm developed on the offshore side of the planed-off area is outlined by black dashed line (compare with field sketch in Figure 3-2B).

D. 23 July 1994. A small storm berm (arrow) has begun to form in the old planed-off area.

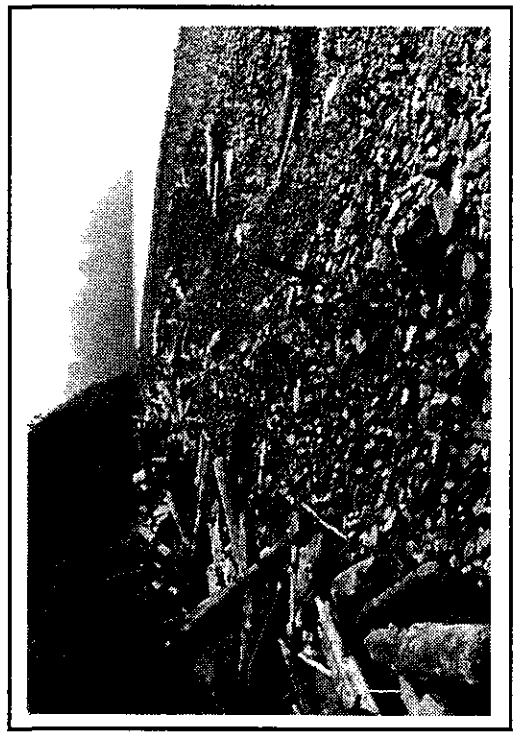


A.

B.



C.



D.

was unchanged, with MOR from 30-70 cm and a layer of heavily oiled sediments (over 12,000 mg/kg oil) occurring below 70 cm. At the time of the August 1992 survey, the subsurface oil had changed little, with sediments described as MOR (13,960 mg/kg) present 40 cm beneath the surface (see Figure 3-5A for profile plot on that day).

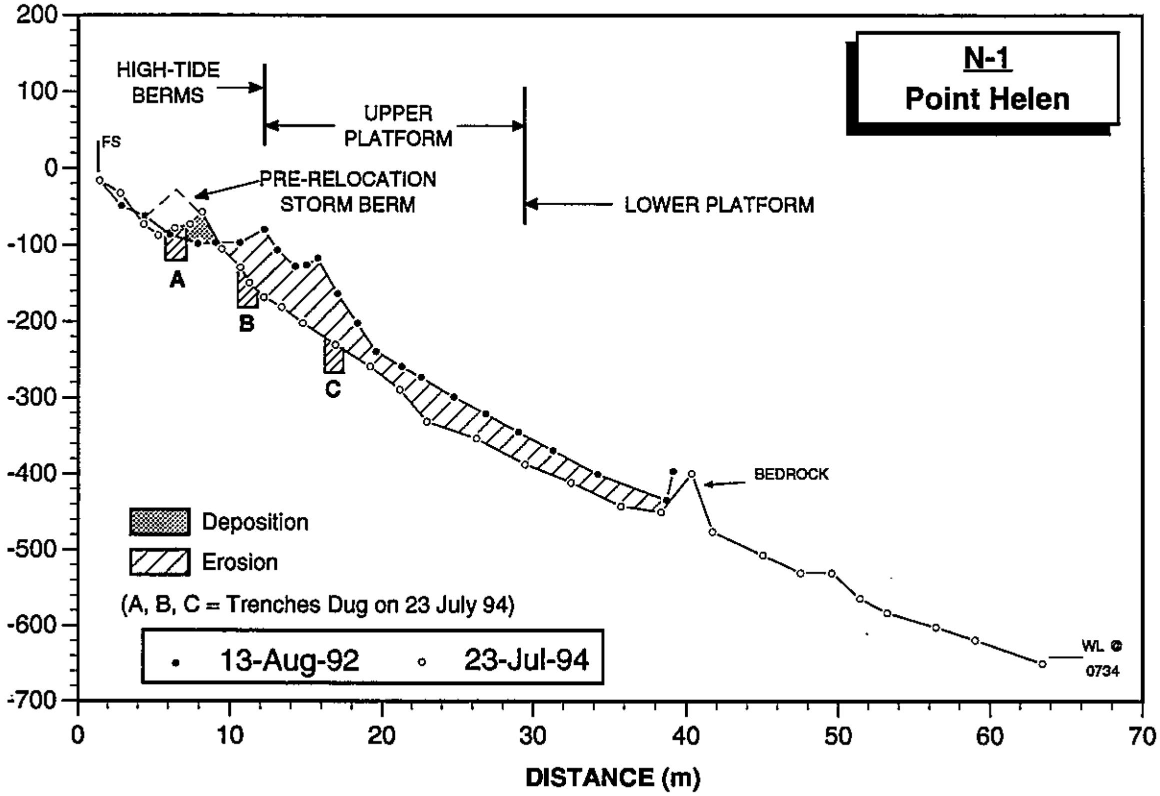
By July 1994, the degree of oiling of the upper zone of sediments had diminished, with only an oily film visible at depths of 45-66 cm in trench C overlying a zone of heavily oiled sediments to greater than 80 cm (Figure 3-6). It should be noted that nearly 70 cm of sediments had been eroded from the beach surface since 1992 (see Figure 3-5A), returning the beach elevation in 1994 to essentially its pre-relocation position (Figure 3-5B). Thus, the apparent increase in 1992 in clean sediment in Figure 3-6 was caused by deposition of a clean sediment berm, which subsequently eroded. Five years later, with the beach profile at nearly the same level as during the spill, heavily oiled sediments containing TPH concentrations of 7,900 and 18,000 mg/kg remain at depths of 66-80+ cm. Total PAHs in these samples were 180 and 360 mg/kg, the highest for the samples collected in July 1994 (see Table 2-2), and higher by a factor of 2-3 than any samples collected in 1992. This deeply penetrated and persistent oil remains relatively unweathered, even after five years (see discussion in Chapter 5). The oil formed a black slick on the water table (Figure 3-8A) and readily sheened. At this site, which is among the most exposed beaches in the Sound, removal by sediment reworking and other processes was effective to 66 cm after five years.

Figure 3-5. **(Facing Page)** Topographic beach profile changes at station N-1 (Point Helen) that illustrate the following:

A. Changes between 13 August 1992 and 23 July 1994. Much of the sediment that had accumulated on the platform as a result of the berm relocation (summer 1991) and the migration of a major shoreline rhythm onto the profile (summer 1992) had been eroded away and a new, relatively small, storm berm had formed.

B. Comparison between 24 May 1990 and 23 July 1994 surveys. The profiles were quite similar except for the fact that the new storm berm was considerably smaller than the original one.

A.


N-1
Point Helen
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
PRE-RELOCATION STORM BERM
FS
A
B
C
BEDROCK
WL @ 0734
Deposition
Erosion
(A, B, C = Trenches Dug on 23 July 94)
13-Aug-92
23-Jul-94
ELEVATION (cm)
DISTANCE (m)

B.

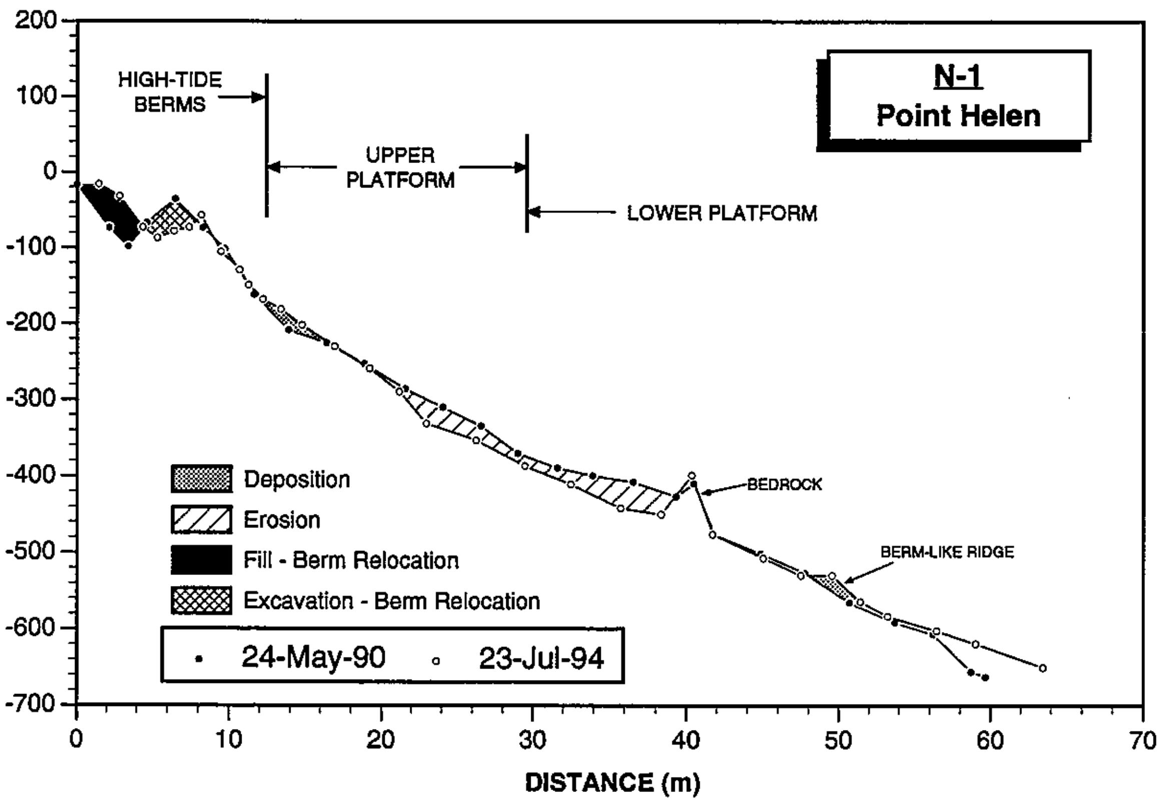

N-1
Point Helen
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
BEDROCK
BERM-LIKE RIDGE
Deposition
Erosion
Fill - Berm Relocation
Excavation - Berm Relocation
24-May-90
23-Jul-94
ELEVATION (cm)
DISTANCE (m)

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

Station	September 1989	May 1990	August 1991	August 1992	July 1994
N-1	95	100	75*	50	5
N-3	100	20	5	0	0
N-4	75	0	0	-	0
N-7	80	5	0	0	0
N-14	90	5	-	0	0
N-15	100	15	60*	1	0
N-17	70	0	0	0	0
N-18	100	5	50*	0	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)	
July 1994	0-50+ (ST)	45-66 (OF) 66-80+ (HOR) 60-65+ (HOR)	

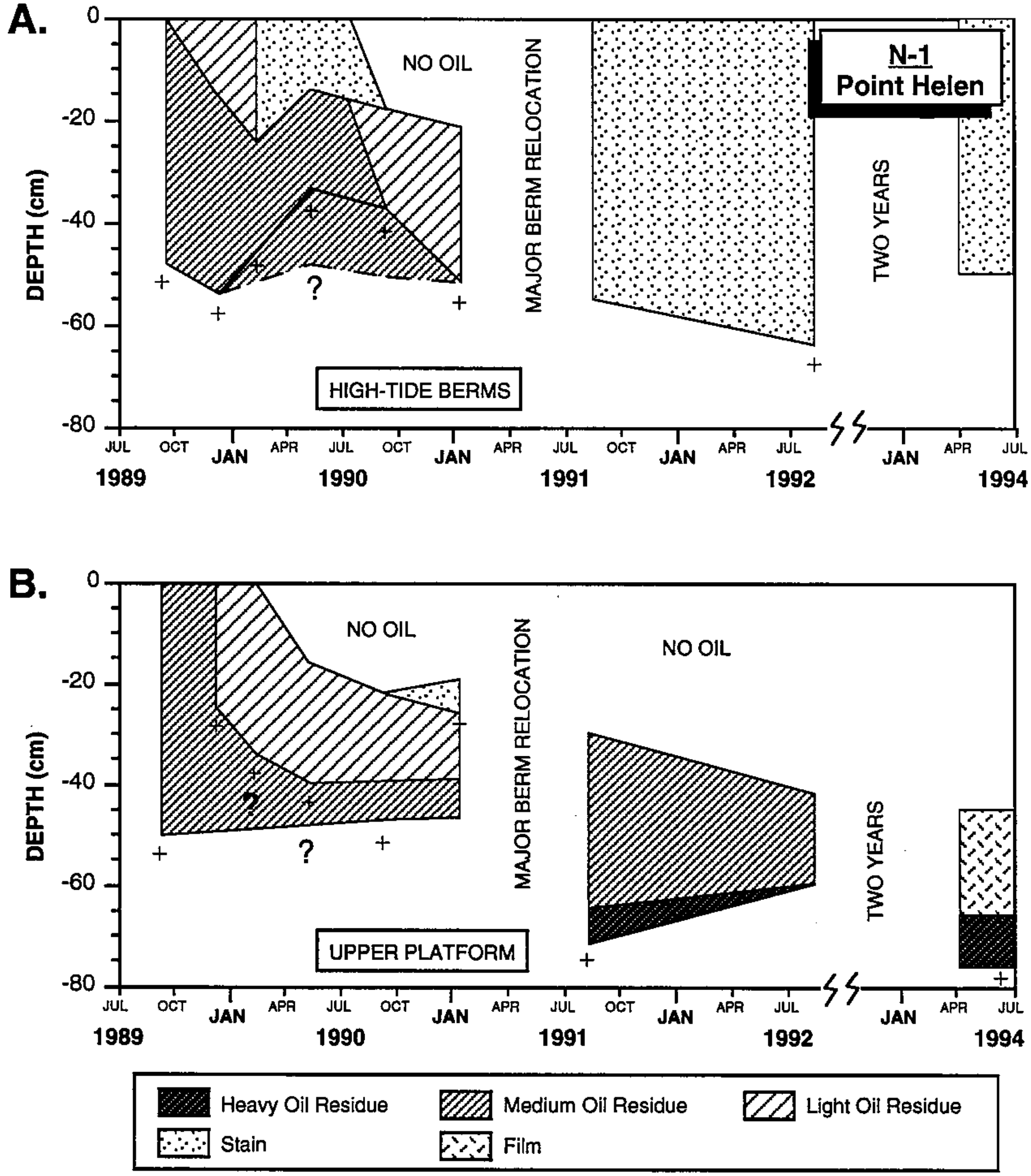
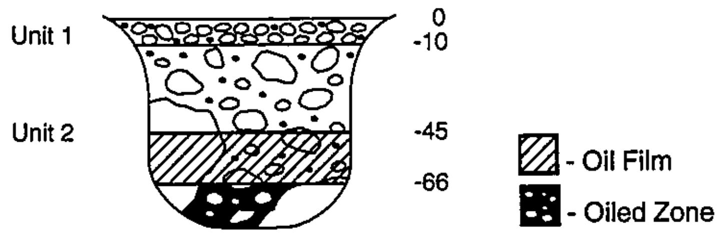
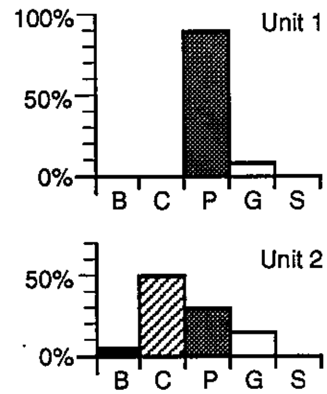


Figure 3-6. Time-series plot of the interval and degree of subsurface oil at station N-1 (Point Helen), based on trench descriptions and chemical analyses, for the (A) high-tide berms and (B) upper platform. See text for explanation of conventions used.

N-1 POINT HELEN, 23 JULY 1994

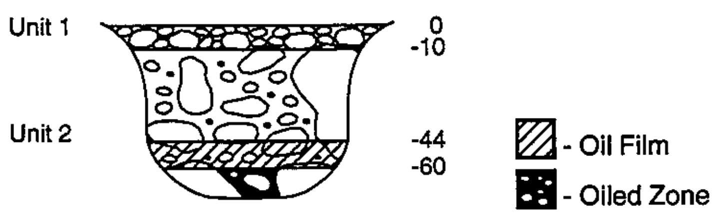
TRENCH B

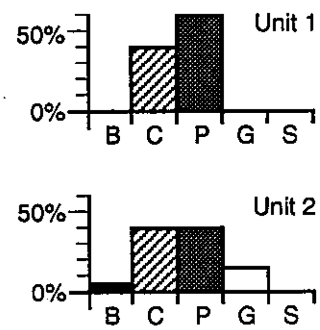




Unit 1: Clean; face of pebble berm.
Unit 2: (OF) at 45-66 cm; (HOR) at 66-80+ cm; oil below formed slick on water table.

TRENCH C





Unit 1: Clean; edge of pebble berm.
Unit 2: (OF) at 44-60 cm; (HOR) at 60-65+ cm; oil below formed black slick on water table.

Figure 3-7. Descriptions for two trenches (B and C) dug at station N-1 (Point Helen) on 23 July 1994 (see Figure 3-1 for location of trenches). Note heavy oil at depth in both trenches. The histograms on the right side are grain-size distributions from boulder (B) to sand (S) for the units delineated in the trench.

Figure 3-8. **(Facing Page)** Photographs of trench C at station N-1 (Point Helen) on 23 July 1994.

A. The heavily oiled interval (HOR) occurred at depths greater than 60 cm in the trench.

B. Close-up of sediments removed from the base of trench, classified as heavy oil residue.

A.

B.

Station N-3 (Smith Island)

Introduction. This station is located on the northwestern end of Smith Island (Figure 1-1) and has a straight-line fetch to the northeast that extends 45-50 km over open water in the Sound, making this one of the most exposed gravel beaches in the study area. The profile, which has been surveyed 12 times, is located just east of a natural groin of bedrock where the island takes an abrupt turn to the southwest. Consequently, the study site is an area of natural accumulation of gravel which has created a rather thick layer of gravel over the underlying bedrock platform, which was uplifted 1.5 m during the 1964 earthquake.

Morphology and sediments. As shown by the beach profile plots and field sketch in Figure 3-9, this station consists of a large storm berm and relatively flat lower and upper platforms that slope 4.5 and 4 degrees respectively. 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. At the time of the survey on 16 August 1992, there were three shore-parallel gravel ridges located on the platforms. These ridges, features observed by the authors only in Prince William Sound and here termed berm-like ridges, are thought to form near the lower three of the four mean levels of stillstand during the tidal cycle, which is marked by a strong diurnal inequality in the Sound: 1) low-high tide; 2) high-low tide; and 3) low-low tide. At the time of the 24 July 1994 survey, the upper two berm-like ridges had been eroded away and the middle portion of the profile was extremely flat (see Figure 3-9). The flat nature of the mid-section of the profile is also illustrated by the photograph in Figure 3-10A. This flattening of the profile is indirect evidence of a period of high wave activity between the two surveys. However, the overlay of the two profiles measured during the 1992 and 1994 field seasons (Figure 3-9B) shows little change except for the erosion of the two berm-like ridges in the middle of the profile and an addition of some gravel in the form

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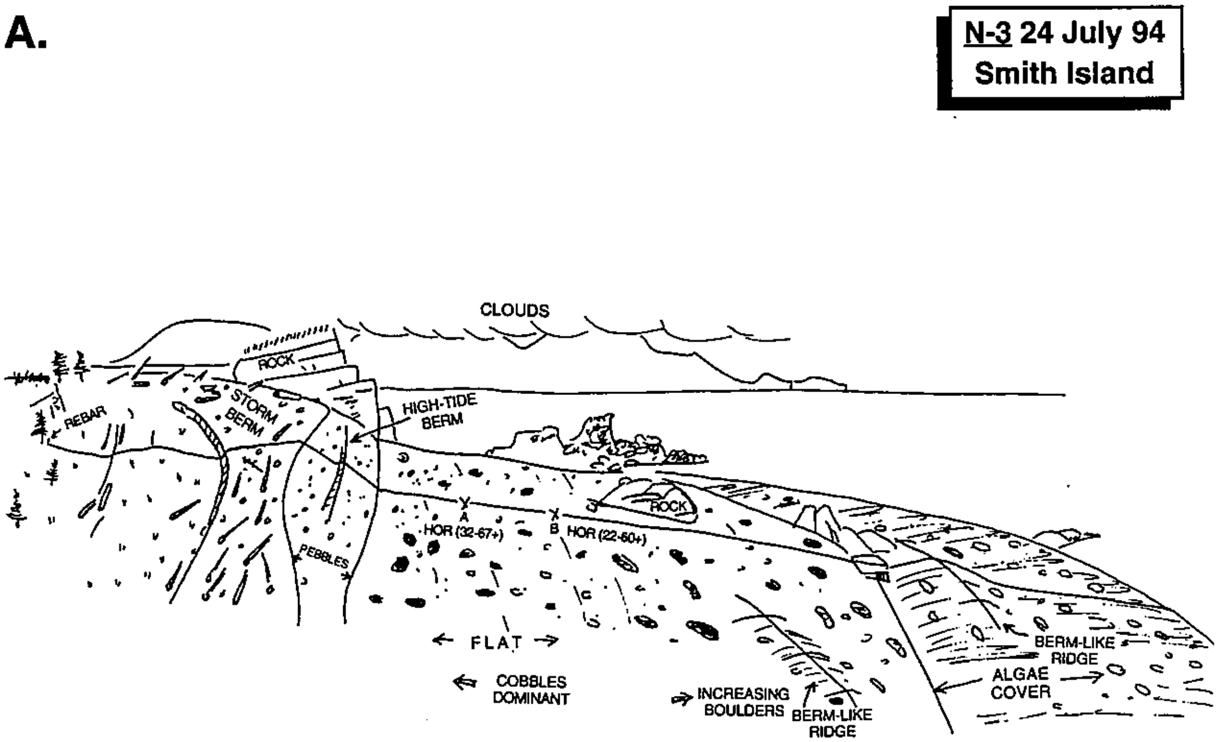
Figure 3-9. **(Facing Page)** Station N-3 (Smith Island).

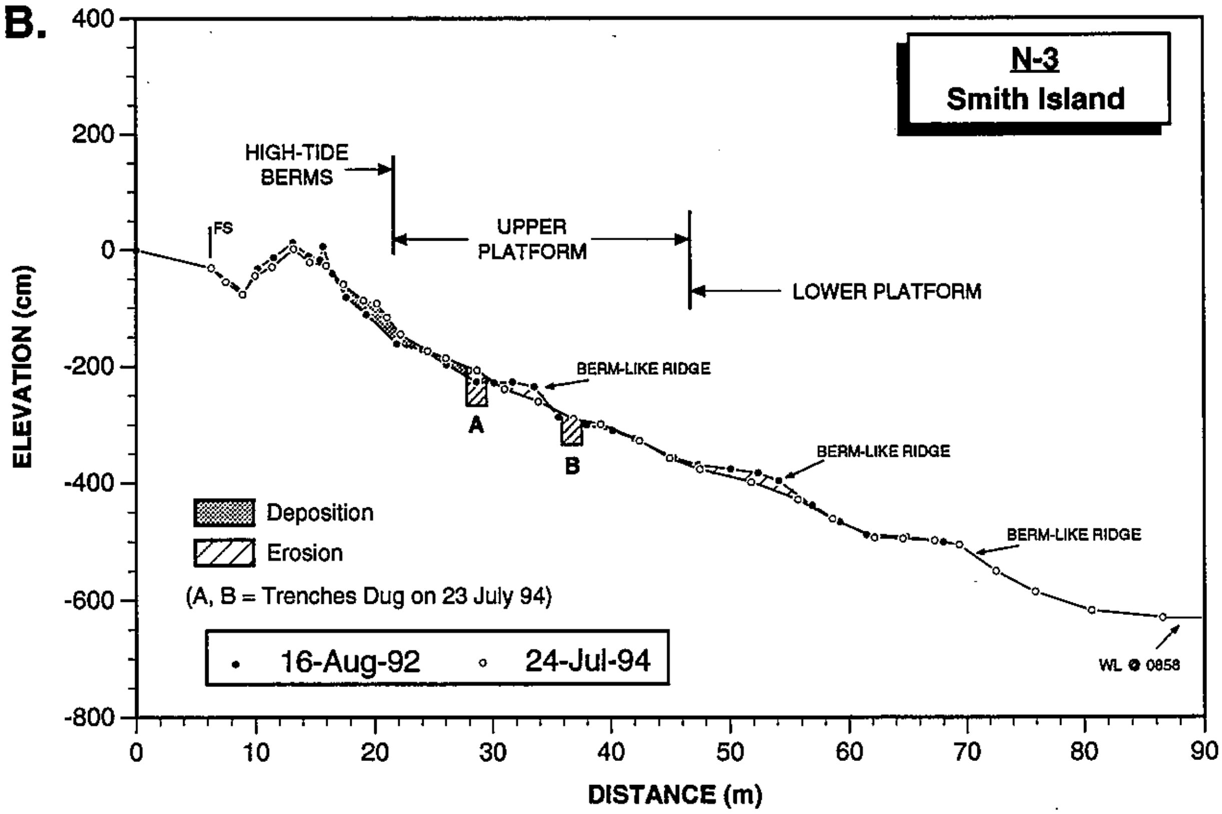
A. Field sketch drawn on 24 July 1994. Note the extremely flat nature of the middle part of the beach.

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

A.


N-3 24 July 94
Smith Island
CLOUDS
ROCK
STORM BERM
REBAR
HIGH-TIDE BERM
ROCK
A HOR (32-67+)
B HOR (22-60+)
PEBBLES
FLAT
COBBLES DOMINANT
INCREASING BOULDERS
BERM-LIKE RIDGE
BERM-LIKE RIDGE
ALGAE COVER

B.


N-3
Smith Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
FS
BERM-LIKE RIDGE
A
B
BERM-LIKE RIDGE
BERM-LIKE RIDGE
Deposition
Erosion
(A, B = Trenches Dug on 23 July 94)
16-Aug-92
24-Jul-94
WL @ 0858
ELEVATION (cm)
DISTANCE (m)
400
200
0
-200
-400
-600
-800
0
10
20
30
40
50
60
70
80
90

of a high-tide berm on the seaward face of the storm berm. Thus, this station continues to show remarkable stability with respect to erosional/depositional trends.

Sediments along the profile increase in size in an offshore direction, with cobbles and pebbles making up most of the upper portion and cobbles and boulders dominating the lower half of the profile. A well-developed coarse gravel armor covers the upper and lower platforms (see photograph in Figure 3-10A). The clasts are subround to round, indicating significant abrasion during wave-generated sediment transport.

Berm relocation. As discussed by Michel and Hayes (1993c), a berm-relocation project was carried out at this site in mid-July 1990. During the berm-relocation process, the seaward face of the high-tide berm was excavated 0.5 to 1.0 m, and the excavated sediments were placed on top of the upper platform. The crest of the berm was not changed in the relocation process. By the time of the 12 January 1991 survey, the excavated area had been completely filled in, and the entire profile had returned to its original configuration. The 26 August 1991 survey revealed that the surface sediment distribution pattern had resumed the distribution it had before the berm-relocation project. The small amount of deposition observed in July 1994 is part of the normal accretion and erosion of berms at the high-tide level.

Surface oil. No surface oil was observed at this station during either the 1992 or 1994 surveys. However, as shown in Table 3-1, this station did retain surface oil longer than any of the other sites classified as cobble/boulder platforms with berms except N-1 (discussed above). During the May 1990 survey, readings as high as 20 percent surface oil were recorded. The highest reading during the August 1991 survey was 5 percent. The reason for these relatively high numbers at such late dates is probably the fact that this was a very heavily oiled station with large amounts of subsurface oil that has continued to leach out, generating chronic sheens.

Figure 3-10. (Facing Page) Photographs of station N-3 (Smith Island) on 24 July 1994.

A. The armored surface of the flat upper platform. Arrows point to the two trenches (A and B) dug at this station.

B. Oil in sediments and on water table at bottom of trench B.

A.

B.

Subsurface oil. The historical summary on subsurface oiling at this station is shown in Table 3-3 and Figure 3-11. Heavy oiling of the subsurface sediments extended all the way to the lower platform to depths of 25 to 30 cm until January 1990. Our survey results showed that there was a major erosional event between the January and March 1990 surveys, which removed 40 to 50 cm of the surface sediments from the profile. As discussed by Michel and Hayes (1991), TPH values in subsurface sediments from the lower platform dropped from 13,450 ppm in January to 520 ppm in March. The oil in the lower platform was removed naturally during the January/March 1990 erosional event because it was less than 30 cm deep.

The degree of oiling in the high-tide berms decreased dramatically during the first non-summer storm period, decreasing from heavy, to moderate, to light over time in the top 25 cm (Figure 3-11A). Below that depth, however, oil concentrations ranged from 3,300 to 22,700 mg/kg through May 1990. The berm-relocation project in the summer of 1990 exposed the subsurface sediments classified as MOR. A sample taken from 25 to 30 cm in the excavation zone during the September 1990 survey contained over 7,600 mg/kg oil. By the time of the January 1991 survey, the excavated sediment had been pushed back up

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)	No oil
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)	
July 1994	No oil	14-47+ (HOR)/4-40+ (HOR)	

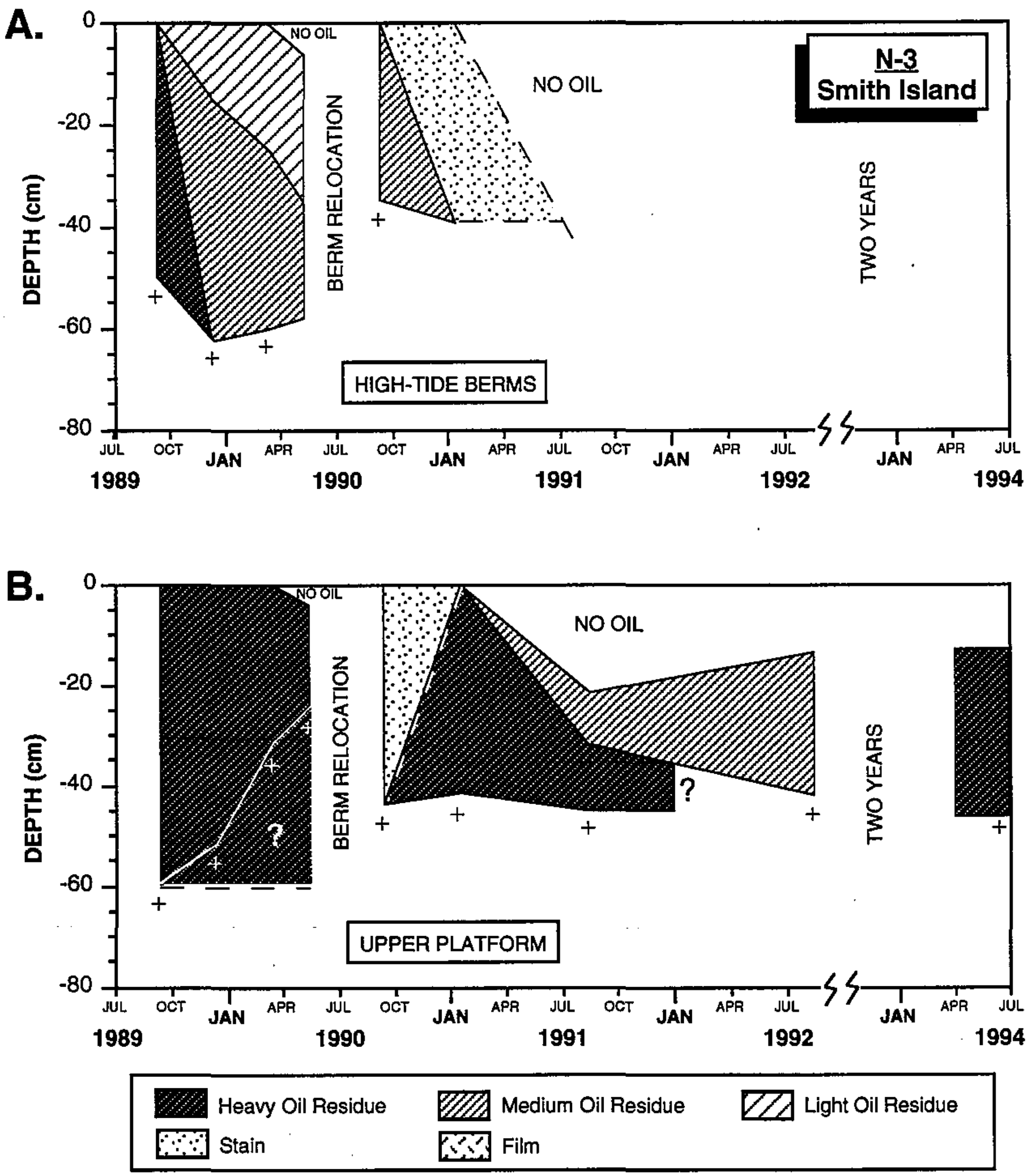


Figure 3-11. Time-series plot of the interval and degree of subsurface oil at station N-3 (Smith Island), based on trench descriptions and chemical analyses, for the (A) high-tide berms and (B) upper platform.

the beach by wave-generated currents, which resulted in the burial of the MOR sediments beneath at least 40 cm of oil-stained cobbles and pebbles. As shown in Figure 3-11A, however, the remaining oil in the subsurface sediments of the high-tide berm area was completely removed by natural processes by the time of the August 1991 survey, and, no oil was found during the 1992 and 1994 surveys.

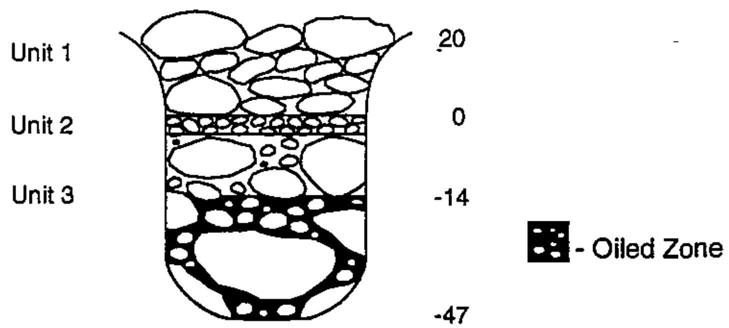
As reported by Michel and Hayes (1993c), the subsurface sediments of the upper platform were heavily oiled initially, containing up to 47,800 mg/kg TPH to depths greater than 60 cm in 1989. Through 1990, TPH concentrations ranged from 4,000 to 16,300 mg/kg, with little differences with depth in each trench. The 44 cm of stained sediments present in this zone in September 1990 (Figure 3-11B) is the result of the piling of excavated sediments on top of the original oiled subsurface sediments during the berm-relocation project in the summer of 1990. By the time of the January 1991 survey, the HOR sediments were exposed at the surface again, because the pile of stained sediments had been returned to their original position in the high-tide berm area. It was not until the August 1991 survey that significant reduction of the sediments classified as HOR was observed, with the top 22 cm of the sediment having been cleaned up by natural processes. Also, there was a 10 cm zone classified as MOR present on top of the HOR sediments below. One would deduce from these changes that significant storm action occurred at this station during the 1990-1991 nonsummer months; however, we have no direct confirming data on this matter.

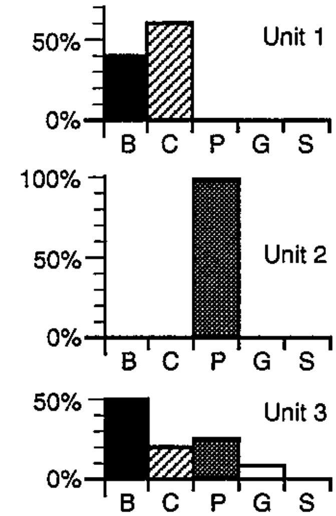
During the August 1992 survey, subsurface oil was still present at about the same depths on the upper platform, but it was classified as MOR in the field. TPH concentrations for the two samples collected were 8,100 and 12,400 mg/kg. A high water table prevented determination of the thickness of the entire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

During the 24 July 1994 survey, subsurface sediments classified as HOR were once again observed in the upper platform at depths of 14-47+ cm in trench A and 4-40+ cm in trench B (see Figure 3-9A for location of trenches and Figure 3-12 for trench descriptions). A sample from 15-25 cm in trench B contained a TPH concentration of 17,000 mg/kg (see Table 2-2). A sample of HOR in trench A from 25-35 cm contained 16,000 mg/kg TPH. These levels were even higher than those measured in 1992, although the 1994 samples were from deeper intervals. Total targeted PAHs were 300 and 250 mg/kg in trenches A and B, respectively, reflecting the lesser degree of weathering this deeply penetrated oil has undergone. There essentially had been little

N-3 SMITH ISLAND, 24 JULY 1994

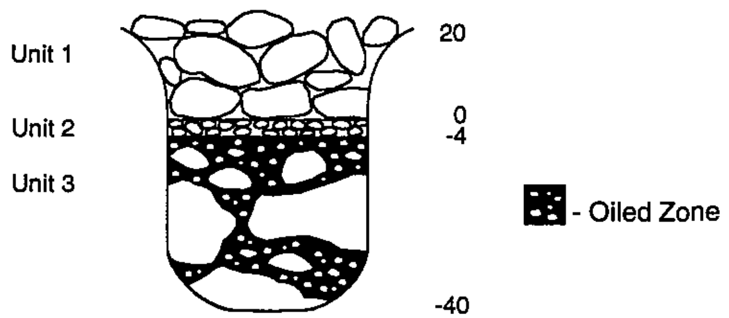
TRENCH A

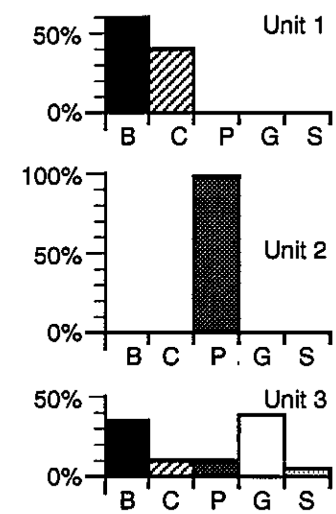




Unit 1: Surface armor of boulders and cobbles.
Unit 2: No oil; zone of pebbles beneath surface armor.
Unit 3: Heavily oiled (HOR) 14-47 cm, not clean below 47 cm; boulders with heavily oiled sediments packed between.

TRENCH B





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

Figure 3-12. Description of trenches A and B at station N-3 (Smith Island) on 24 July 1994, showing presence of heavy subsurface oil under conspicuous surface armor. See Figure 3-9A for location of trenches.

change in the degree and extent of the zone of subsurface oil since 1991. The subsurface oil generated chronic sheening at this site, visible as silver sheens in the ground water draining from the beach during the falling tide.

The distribution of the subsurface oil is illustrated by the two trench sketches in Figure 3-12, and the oiled sediments in the bottom of trench B are pictured in the photograph in Figure 3-10B. Note that the top 20 cm consisted of 40-60 percent boulder and the remaining was cobbles. Even with depth, the sediments were very coarse. However, there was enough pebble- and granule-sized sediments to slow removal by tidal and groundwater flushing.

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

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

2) The well-developed armor of cobbles and boulders over the subsurface sediments, which prevents wave action from reworking the deeper sediments. These deeper sediments have a large granule fraction which holds the oil.

3) The relatively low angle of the slope of the rock platform (4.3 degrees), which partially explains why tidal flushing has been slower at this station than at those stations with steeper slopes (e.g., N-17 on Perry Island and N-4 on Smith Island, which have upper platforms that slope offshore at 6 degrees).

4) The heavy initial oiling of the site.

Station N-4 (Smith Island)

Introduction. This station is located one-third of the way from the east end of Smith Island (Figure 1-1). It has a similar physical setting to station N-3, with a fetch of 40-45 km in a northeasterly direction. Although the 1994 study was the eleventh time the beach had been surveyed, it had not been visited since August 1991, a three-year absence.

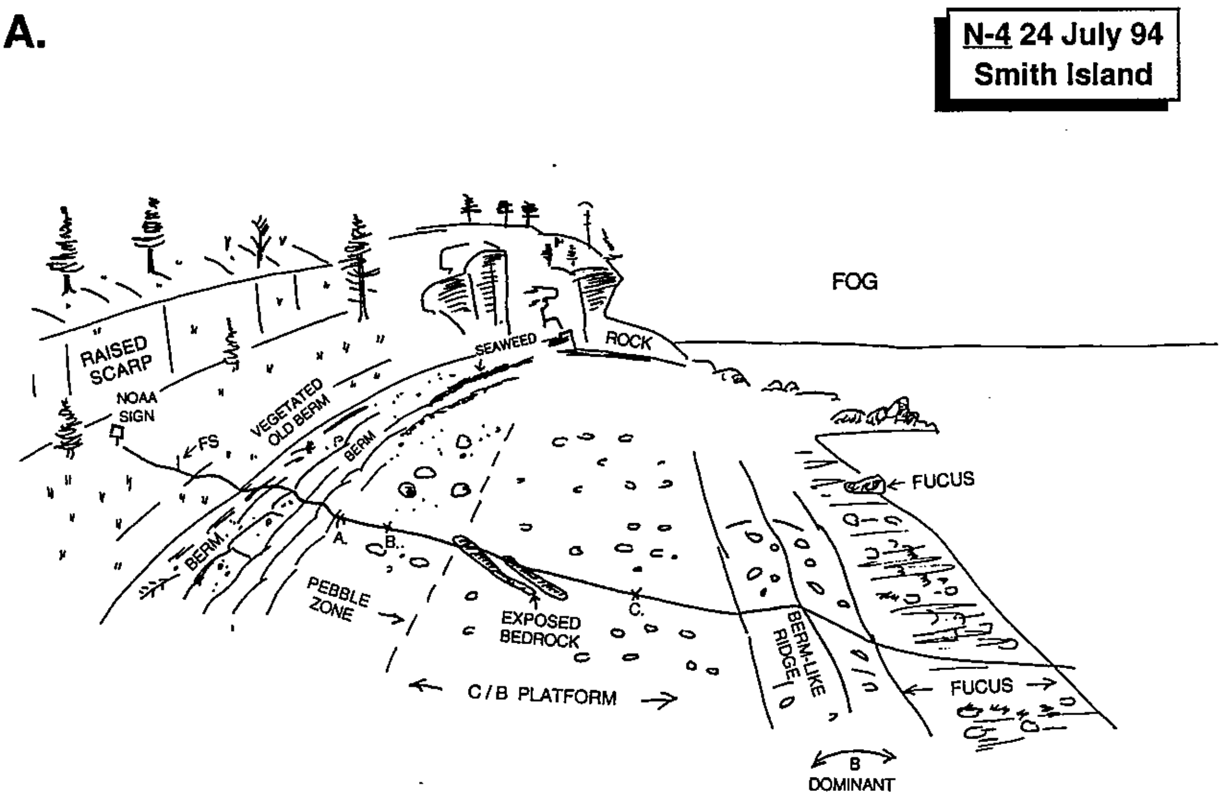
Morphology and sediments. The general morphology of this beach is illustrated by the profile plots and field sketch in Figure 3-13. The beach is primarily an uplifted rock platform (uplifted 1.5 m during 1964 earthquake) with minor berms at the high-tide line.

Figure 3-13. (Facing Page) Station N-4 (Smith Island).

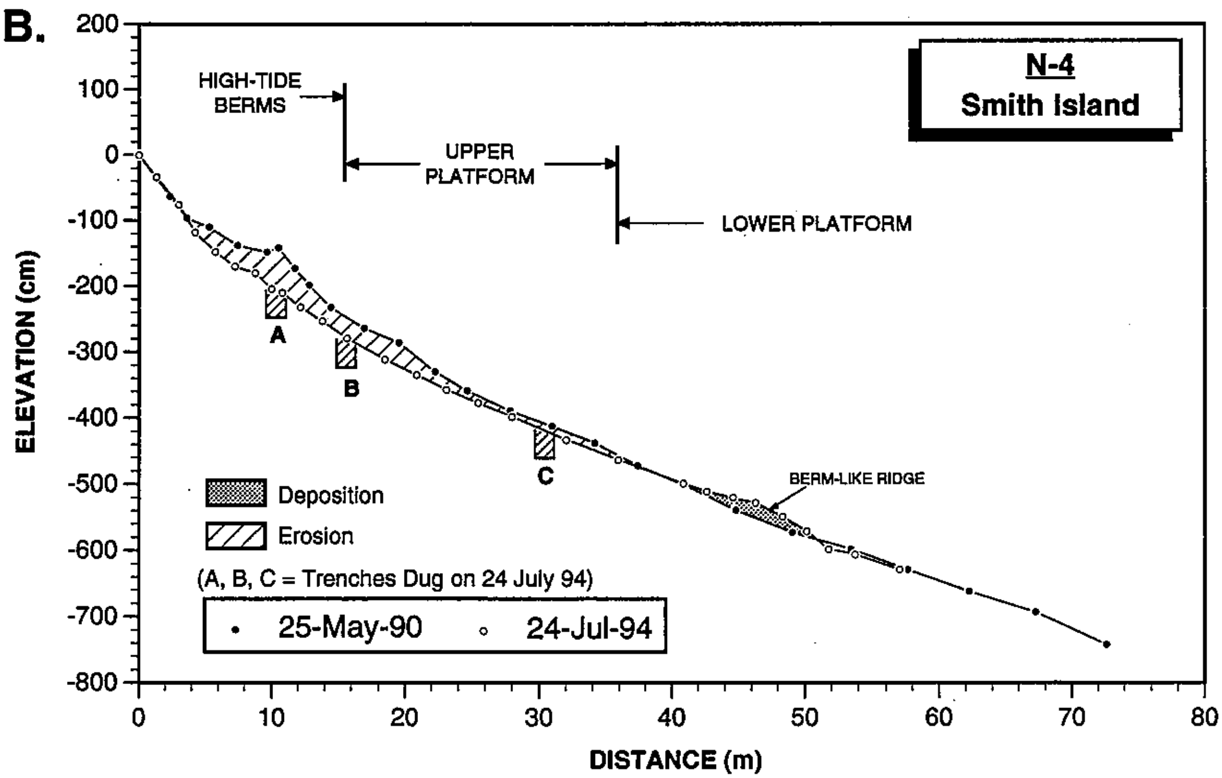
A. Field sketch on drawn on 24 July 1994. Note exposed bedrock in the middle of the beach and large berm-like ridge.

B. Beach profiles at station N-4 (Smith Island) measured during the surveys of 25 May 1990 and 24 July 1994 plotted at a 5:1 vertical exaggeration. Note that the entire profile was erosional in 1994 in comparison with the 1990 survey except for the formation of a new berm-like ridge on the lower one-third of the profile.

A.


N-4 24 July 94
Smith Island
FOG
RAISED SCARP
NOAA SIGN
FS
VEGETATED OLD BERM
BERM
SEAWEED
ROCK
FUCUS
BERM
A.
B.
C.
PEBBLE ZONE
EXPOSED BEDROCK
C / B PLATFORM
BERM-LIKE RIDGE
FUCUS
B DOMINANT

B.


N-4
Smith Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
ELEVATION (cm)
DISTANCE (m)
A
B
C
BERM-LIKE RIDGE
Deposition
Erosion
(A, B, C = Trenches Dug on 24 July 94)
25-May-90
24-Jul-94
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0
10
20
30
40
50
60
70
80

There is not a well-developed gravel storm berm and the beach is backed by a raised vertical scarp (see field sketch in Figure 3-13B). As pointed out by Michel and Hayes (1991), sediment appears to be in relatively short supply in comparison to the nearby station N-3, as seen by the sparse sediment in the berms and abundance of exposed bedrock along the uplifted rock platform. As shown in Figure 3-14, there is an abrupt change in sediment grain size at about mean sea level (20 m from the start of the profile), with finer gravel dominating the upper half of the intertidal zone and a heavy boulder armor the lower half. A single, large boulder-dominated berm-like ridge usually occurs on the lower one third of the profile. The pebbles on the upper half of the beach are highly mobile; we have observed several cycles of construction and erosion of spring and neap berms during the study period.

Berm relocation. A berm relocation project was carried out at this site during the summer of 1990. As can be seen from the profile plots in Figure 3-15A, this berm-relocation project was conducted entirely within the upper intertidal zone. By the time of the 21 January 1991 survey, the excavated pit at the high-tide line had been completely refilled by wave action, but about half of the relocated sediment had been eroded from the profile and presumably deposited on a high cuspate berm at the western side of the beach (Michel and Hayes 1993a). The survey of 26 August 1991 showed that the profile had changed very little since the January 1991 survey, except for the construction of a large berm-like ridge on the lower platform. The August 1991 survey is compared with the September 1990 (immediately post berm-relocation) profile in Figure 3-15B.

The three surface sediment grain-size plots in Figure 3-14 show the response of the beach to the berm-relocation project. The 1 September 1990 plot shows that some finer sediments (i.e., granule and pebbles) extended well down the beach and over the entire upper platform. By the time of the 26 August 1991 survey, however, the amount of pebbles had decreased and more of the sediment on the upper platform consisted of cobbles and boulders. At the time of the 24 July 1994 survey, the beach showed the typical coarsening offshore distribution pattern exhibited by all of the cobble/boulder platforms with berms that have not been modified by man.

The above information indicates that this beach was an ideal site for a berm-relocation project because of the exceptional mobility of the sediments. However, examination of the profile plots in Figure 3-16 raises a question about the long-term impact of the project on the beach with respect to its erosional characteristics. Figure 3-16A presents a comparison of the 1 September 1990 survey, which was conducted shortly

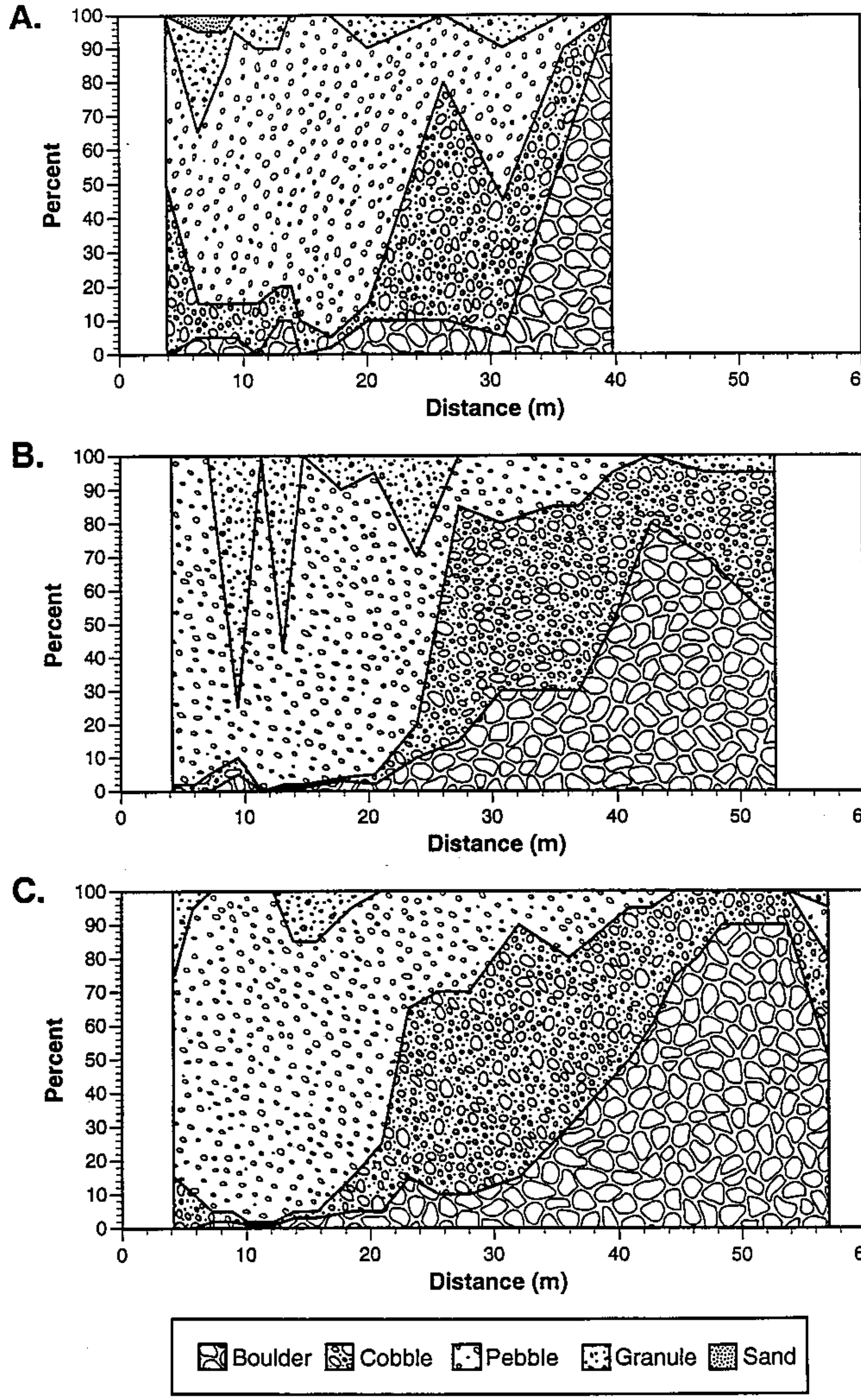


Figure 3-14. Distribution of surface sediments within the intertidal zone of station N-4 (Smith Island), based on visual estimates at each survey point along the profile: (A) 1 September 1990; (B) 26 August 1991; and (C) 24 July 1994. The plot in A was measured shortly after the berm-relocation project of the summer of 1990.

after the berm relocation, and the most recent survey, conducted on 24 July 1994. This plot shows that all of the sediment excavated from the pit in the area of the high-tide berms and placed down the beach had been completely eroded away by the time of the 1994 survey. As stated above, about half of this sediment was eroded away during the nonsummer storm season of 1990-1991, which the surveys at station N-3 indicate was a period of significant erosion (discussed above). The comparison of the profiles measured during the last two surveys, 26 August 1991 and 24 July 1994, given in Figure 3-16B illustrates the continuing trend of erosion at this station, with the beach being in the most erosional condition of any time during the study when the July 1994 survey was conducted. It is not known if the berm relocation is related to this erosional process.

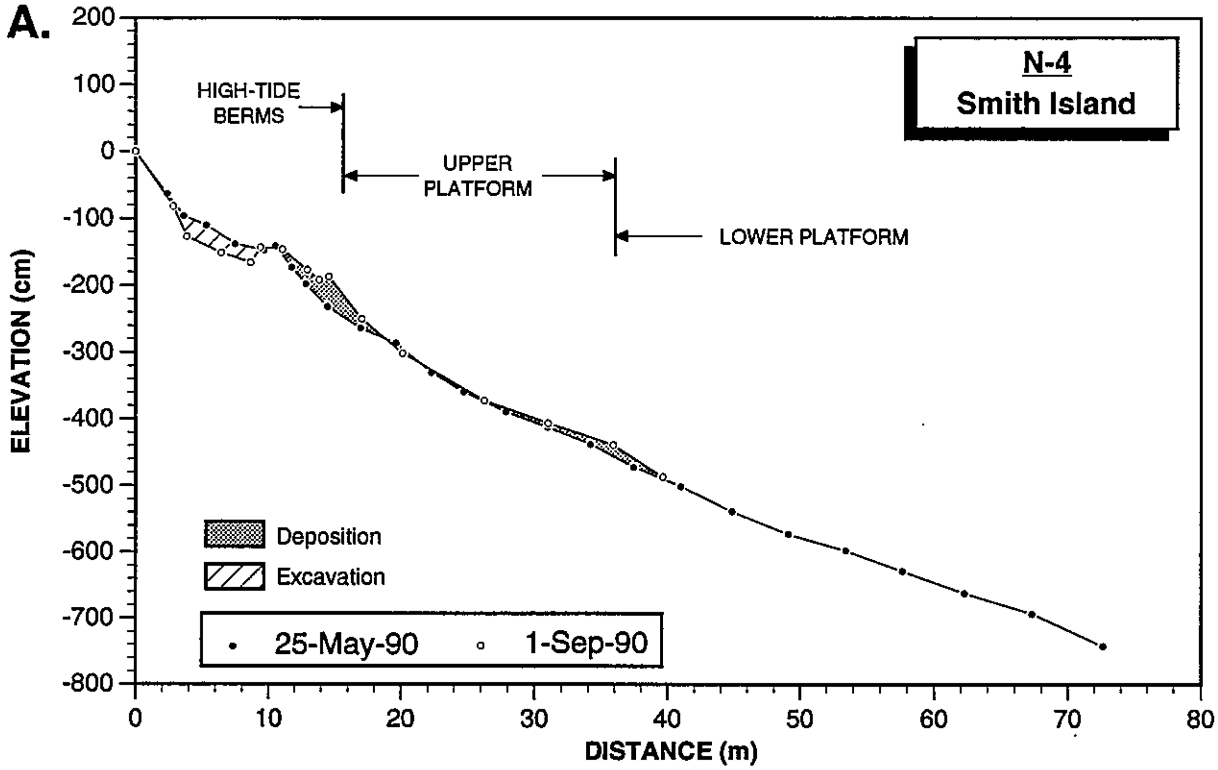
Surface oil. The surface oil on this beach was completely removed during the non-summer storm season of 1989-1990. No surface oil was observed during the May 1990 survey nor at any time since. The high degree of mobility of the surface gravel at this site probably accounts for the rapid removal of the surface oil once cleanup was terminated.

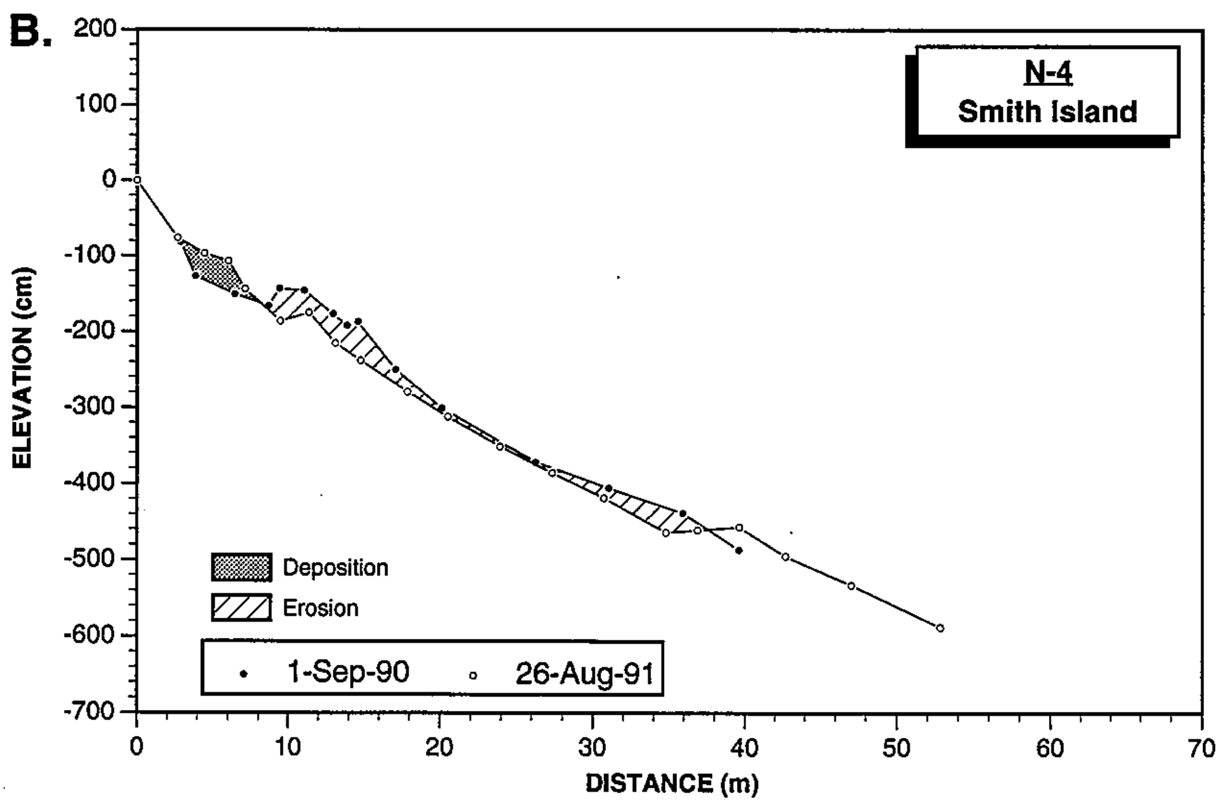
Subsurface oil. Data on the oiled subsurface sediments at this site indicates that the berm relocation aided the natural removal of the subsurface oil in the high-tide berm portion of the beach. No oil was observed in the vicinity of the high-tide berms at the time of the August 1991 survey. On the other hand, subsurface oil was found on the upper platform during the 26 August 1991 survey (MOR sediments between 25 and 35 cm in one trench). However, that subsurface oil must have had a patchy distribution, because it was not found in the trenches dug during the May 1990 and January 1991 surveys. No subsurface oil was found in any part of the beach during the 24 July 1994 survey.

It is significant that the subsurface oiled sediments on this beach were cleaned up much more quickly by natural processes than that at its neighboring beach, N-3, although the dynamic setting is quite similar. The probable causes for these differences are:

1) The sediments are thicker and somewhat coarser, particularly on the upper half of the profile, at N-3. Thus, the subsurface oil could penetrate deeper and the sediments were not as mobile at N-3 as at N-4.

Figure 3-15. (Facing Page) Beach profiles at station N-4 (Smith Island) measured during the surveys of 24 May 1990/1 September 1990 (A) and 21 January 1991/26 August 1991 (B) plotted at a 5:1 vertical exaggeration. Note rapid recovery of the profile after the summer 1990 berm-relocation project.


A.
N-4
Smith Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
ELEVATION (cm)
DISTANCE (m)
Deposition
Excavation
25-May-90
1-Sep-90


B.
N-4
Smith Island
ELEVATION (cm)
DISTANCE (m)
Deposition
Erosion
1-Sep-90
26-Aug-91

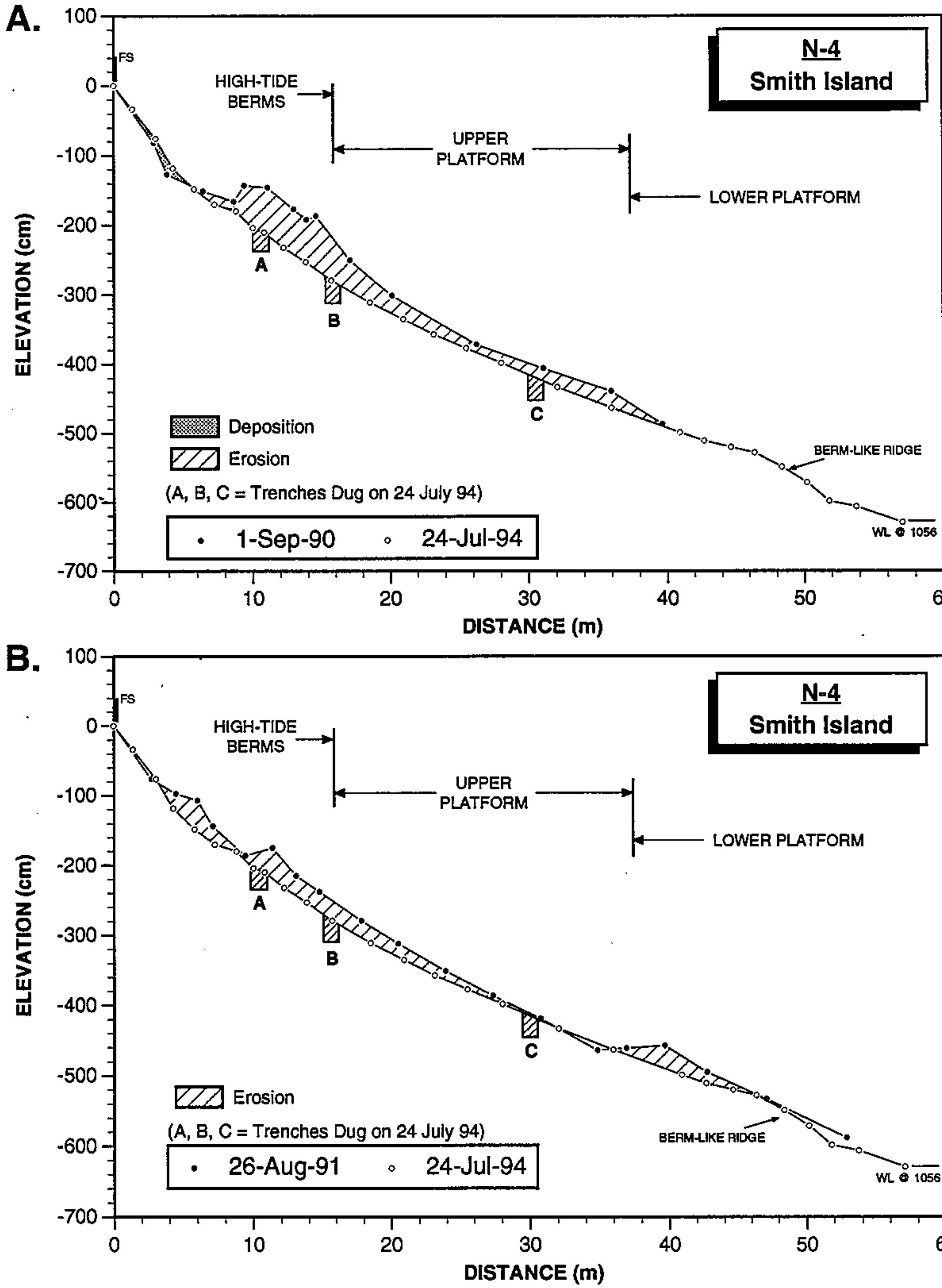


Figure 3-16. Beach profiles at station N-4 (Smith Island) on 1 September 1990/24 July 1994 (A) and 26 August 1991/24 July 1994 (B) plotted at a 5:1 vertical exaggeration. Note the large pile of excavated sediment on the September 1990 profile (A). This beach appears to have been in an erosional mode for some time.

2) The rock platform is closer to the surface and slopes at a greater angle (6 degrees as opposed to 4.3 degrees) at N-4, which probably enhanced tidal flushing of the oil at that site.

Station N-7 (Knight Island)

Introduction. Although this station contains a very large storm berm (Figure 3-17), it appears to be more sheltered than the other stations in this class from all but major storms. The fetch perpendicular to the beach is only 8 km, but open effective fetches of 15 to 20 km to the northeast (40 degrees to beach) and 60 km to the east-northeast (60 degrees to beach) allow for significant wave activity during major storms. The 25 July 1994 survey marked the eleventh time this station had been surveyed.

This beach was one of the sites selected in 1990 for monitoring the effectiveness of bioremediation on the subsurface oil. Our profile line was 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 the oleophilic fertilizer Inipol.

Morphology and sediments. The morphology of this beach is illustrated by the field sketch and profiles in Figure 3-17. The high-tide berms at this station, which are composed of pebbles and cobbles, have showed considerable mobility throughout the various surveys. At the time of the 25 July 1994 survey, the area of the high-tide berms and part of the upper platform showed about 30 cm of erosion in comparison with the profile run on 15 August 1992 (Figure 3-17B). This type of change has been a common occurrence during the earlier surveys. However, the other parts of the profile, the storm berm and the cobble-boulder platform, have showed very little change throughout the study. Berm-like ridges have been notably absent from this profile, though a fairly subtle one was present on the lower platform during the 1994 survey (Figure 3-17A). The absence of these features probably reflects the absence of frequent storm waves on this beach.

The sediments at station N-7, 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. An armor of coarse gravel is very well-developed on both the upper and lower platforms, which slope offshore at relatively low angles for the raised shore platforms of Prince William Sound (5 and 3 degrees, respectively). The armored surface of the platforms is illustrated by the photograph in Figure 3-18.

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 anyway (discussed below).

Surface oil. At the end of the first summer after the spill, the upper third of this beach was 45 to 100 percent covered by surface oil. Only 5 percent of surface oil remained at the time of the May 1990 survey, and no surface oil was observed at this site from the time of the August 1991 survey forward.

Subsurface oil. Table 3-4 and Figure 3-15 summarize the extent and degree of subsurface oil at this station. The complex pattern of subsurface oiling for the high-tide berms shown in Figure 3-19A reflects the high mobility of the sediments in that area. This pattern, discussed in detail by Michel and Hayes (1993c), shows that heavy oil (6,600 mg/kg) extended from the surface to more than 20 cm in the pebble berms in September 1989, but only stained sediments were present by the time of the May 1990 survey. The subsurface oil had been completely removed from the high-tide berms by natural processes at the end of the second storm season.

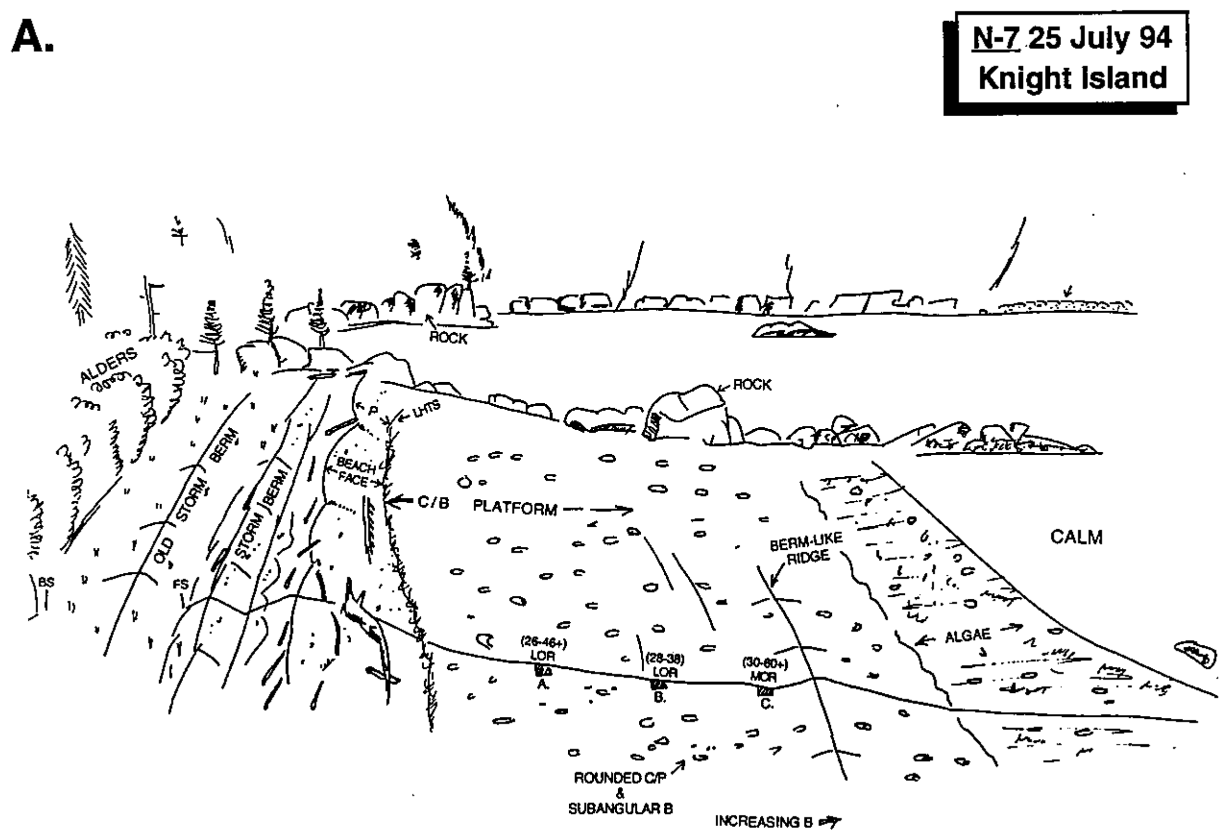
As at station N-3, heavy oiling at this station extended all the way to the lower platform and remained there until the January 1991 survey (see Table 3-4). The subsurface oil was characterized as heavy (averaging around 10,000 mg/kg) throughout that period, in both the upper and lower platform sediments. The large and stable armor of cobbles and boulders presumably slowed the natural removal processes, in spite of heavy application of Customblen fertilizer during 1990 as part of the monitoring study to determine the effectiveness of nutrient addition conducted at this beach. Oiled subsurface sediments were not observed on the lower platform after the January 1991 survey.

Figure 3-17. (Facing Page) Station N-7 (Knight Island).

A. Field sketch on 25 July 1994.

B. Comparative beach profiles for surveys conducted on 15 August 1992 and 25 July 1994. Note erosion in the high-tide berm and upper platform area.

A.


N-7 25 July 94
Knight Island
ALDERS
ROCK
ROCK
P
LHTS
BEACH FACE
C/B
PLATFORM
OLD STORM BERM
STORM BERM
BS
FS
CALM
BERM-LIKE RIDGE
ALGAE
(26-46+) LOR A.
(28-38) LOR B.
(30-60+) MCR C.
ROUNDED C/P & SUBANGULAR B
INCREASING B

B.

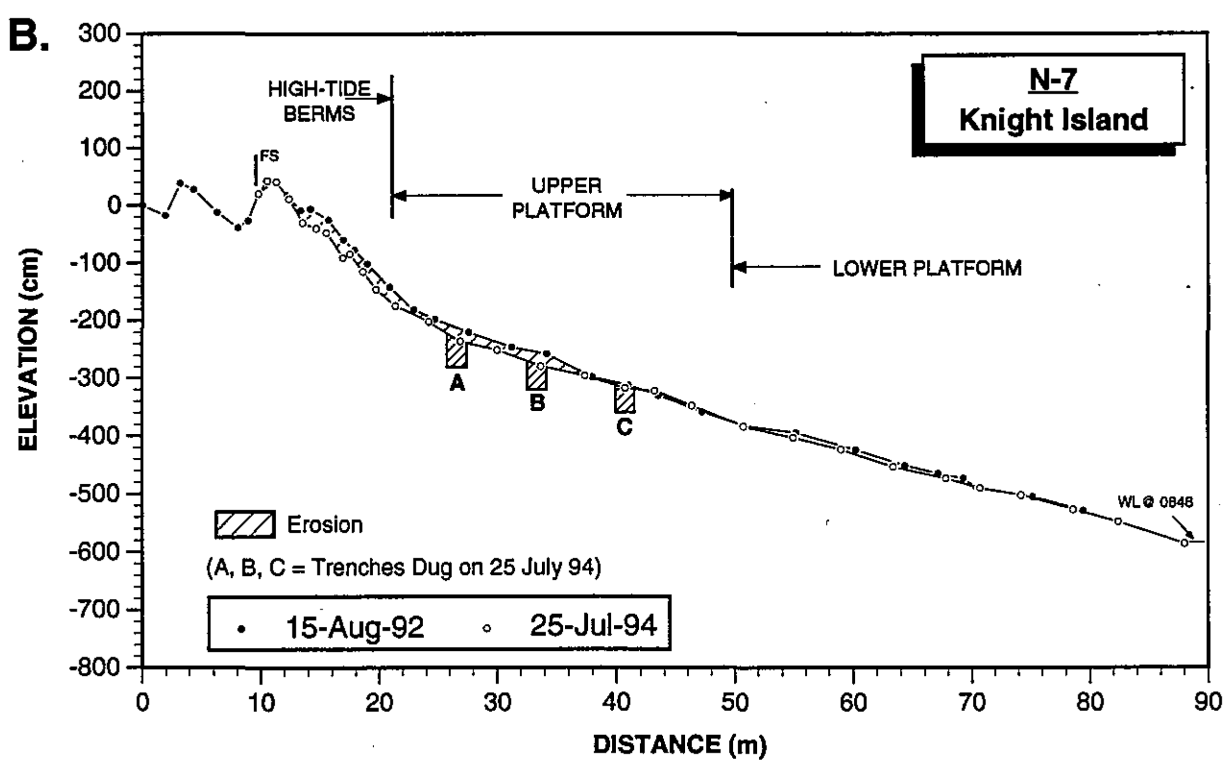

N-7
Knight Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
FS
A
B
C
WL @ 0848
Erosion
(A, B, C = Trenches Dug on 25 July 94)
15-Aug-92
25-Jul-94
ELEVATION (cm)
DISTANCE (m)
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0
10
20
30
40
50
60
70
80
90

Figure 3-18. Photograph of station N-7 (Knight Island) on 25 July 1994. View down profile from the high-tide line. Arrows point to the location of the three trenches dug at this station (A, B, and C). Note uniform surface armor of coarse gravel.

The data on oiling of the subsurface sediments of the upper platform given in Figure 3-19B illustrate the persistence of heavily oiled sediments to depths of at least 75 cm, with heavy oil right to the surface just below the armor, through January 1991. The first clean subsurface sediments observed on the upper platform were encountered during the August 1991 survey, when the top 15-30 cm of sediment below the armor were visually clean. Sediments below those depths remained heavily oiled with samples averaging 7,500 mg/kg of oil, about 25 percent lower than during the previous surveys.

As reported by Michel and Hayes (1993c), during the August 1992 survey the clean upper sediments averaged about 15 cm in thickness. Below that were MOR sediments that ranged between 14,700 and 18,700 mg/kg oil, the highest values measured during the 1992 survey. The oil in these heavily oiled sediments was among the most intensely weathered of the samples taken during the 1992 survey. The reason for such intense weathering is unknown.

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	No oil	14-42 (MOR)/16-48+ (MOR)	
July 1994	No oil	26-42+ (LOR) 28-48 (LOR) 30-55 (MOR)/55-60+ (HOR)	

Oil was encountered in all trenches dug in the upper platform during the 25 July 1994 survey (see trench sketches in Figure 3-20). However, the degree of oiling had dropped to LOR in the two upper trenches A and B, based on our visual estimates. TPH for three samples from these trenches ranged between 600 and 3,300 mg/kg (Table 2-2), so these sediments still contained significant amounts of oil. The total PAH concentrations were extremely low (1.6-3.8 mg/kg) compared to the TPH levels, reflecting the extent of PAH weathering of these oil residues. Also, the layer of clean sediments above the oiled zone was about 15 cm thicker on the average than it had been during the 1992 survey, even though the topographic survey showed little change of the beach level, except for some minor erosion. Thus, there had been further natural removal to depths of 28 cm below the armor after five years.

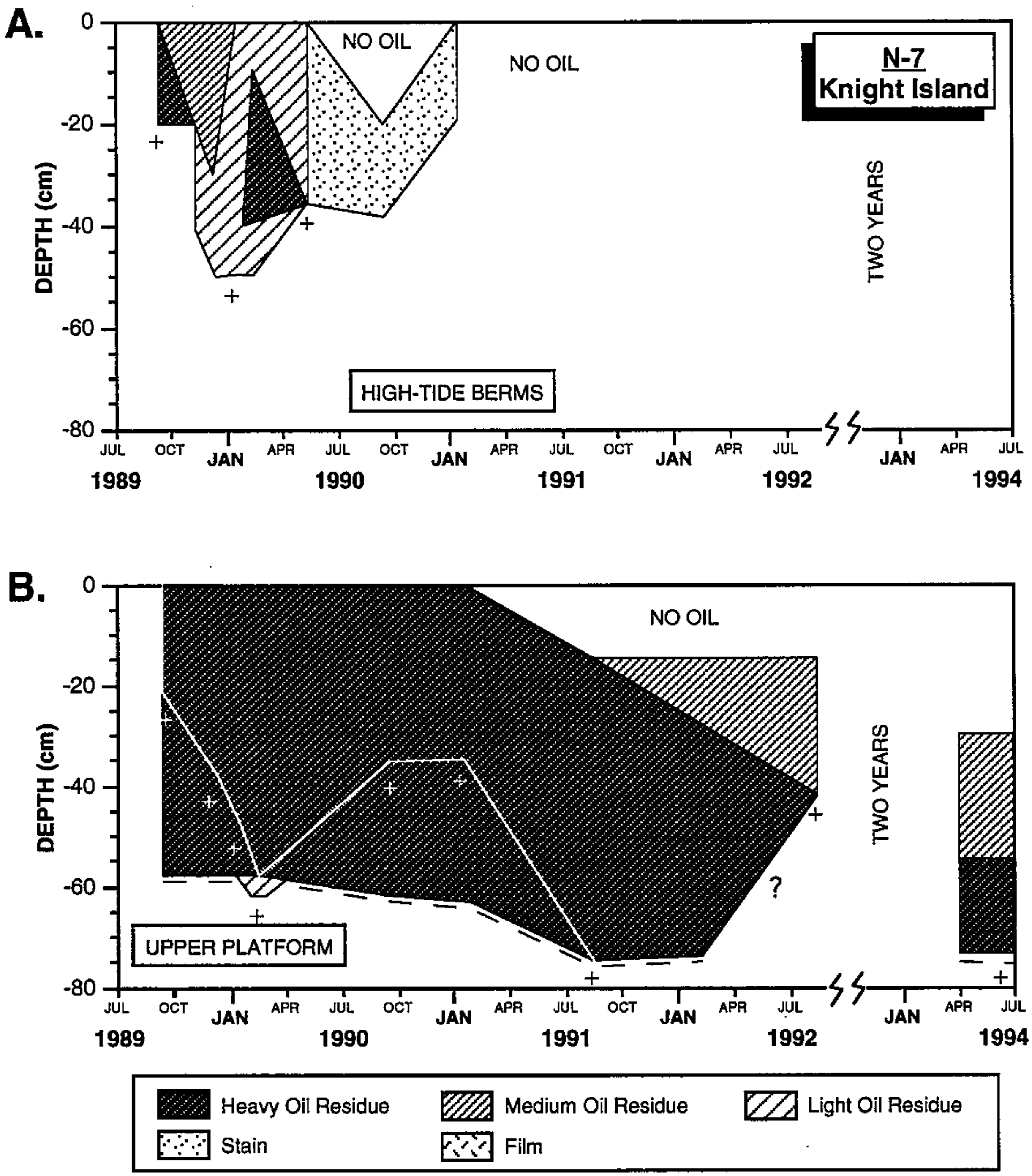


Figure 3-19. Time-series plot of the interval and degree of subsurface oiling at station N-7 (Knight Island), based on trench descriptions and chemical analyses, for (A) high-tide berms, and (B) upper platform. Note the near-complete removal of subsurface oil from the high-tide berms after the first storm season, and the persistence of oil in the subsurface sediments of the upper platform through July 1994.

The oil distribution in trench C was different than the upper two (see location of trenches in Figure 3-17A and descriptions in Figure 3-20). MOR was observed at 30-55 cm below the armor (containing 4,500 mg/kg TPH), with HOR below that to at least 60 cm. A sample of HOR at the bottom of the trench had 7,700 mg/kg TPH, yet PAH were only 17 mg/kg. This trench showed some improvement, compared with 1992 observations as shown in Figure 3-19B. The TPH levels in 1992 ranged from 14,700 to 18,700 mg/kg, compared to levels averaging about 4,000 mg/kg in 1994, a reduction of about 75 percent.

This station has always proved to be puzzling and informative, as the following remarks from Michel and Hayes (1991) indicate: "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 this 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". Five years after the spill, the beach still retained a considerable amount of subsurface oil, but it seemed to be decreasing and weathering more than the oil at stations N-3 and N-1. The prediction on the mobility of the armor appears to hold, except possibly for the lower platform during storms in early 1991, when the subsurface oil was removed from that area. Some factor not related to dynamic coastal processes appears to be removing the subsurface oil from the upper platform at this station.

One possibility is that the higher chemical weathering and physical removal at this site are related to the application of fertilizer during the 1990 tests with Customblen and Inipol. However, both types of fertilizers were applied to other beaches. Application rates at N-7 were within the guidelines for widescale application (Prince et al. 1990). The profile line was the boundary between the fertilized and unfertilized areas, although Inipol was applied to the entire segment on 8 September 1990, using standard application rates. This station was the only gravel beach in our monitoring program that received two applications of Customblen in 1990. Even for samples collected as early as August 1991, station N-7 samples were more extensively weathered than other gravel beaches (Michel and Hayes 1993a). There does not appear to be any geomorphic or hydrologic difference between N-7 and other gravel beaches to explain the higher degree of weathering of the subsurface oil.

Station N-15 (Latouche Island)

Introduction. Located near the center of a northwest-southeast oriented pocket beach on the northeast corner of Latouche Island (Figure 1-1), this gravel beach has a fetch of only 25 km perpendicular to the beach, but one of 40 km in the north-northeast direction (70 degree angle to beach). Therefore, it is subject to considerable wave action. The beach was uplifted 3.5 m during the 1964 earthquake, the maximum for any of our study sites, and the gravel veneer is underlain by a reddish, fine-grained sediment. On 23 July 1994, we surveyed the beach for the thirteenth time.

Morphology and sediments. The morphology of the beach at N-15 at the time of the 23 July 1994 survey is illustrated by the field sketch and profile plot in Figure 3-21. Except for a couple of low-amplitude high-tide berms, the beach was exceeding flat in July 1994, as shown by the photograph in Figure 3-22A. This beach usually contains several berm-like ridges on the upper and lower platforms. There were three such ridges located along the profile at the time of the 13 August 1992 survey. The profile measured on that date overlies the 1994 plot in Figure 3-21B, illustrating the complete removal of the ridges before the later survey. Also, the high-tide berm zone was quite wide during the 1992 survey, with three berms being present. As shown by the overlay plot in Figure 3-21B, however, the lower two of these berms were missing in July 1994.

The sediments on this beach were studied more than those of any of the other exposed gravel beaches, and the results are summarized in detail in Michel and Hayes (1991). Grain size increases in an offshore direction, with pebbles and cobbles dominating the high-tide berm area and boulders and cobbles being the most abundant sediment type on the platforms. This station has always shown strong armoring on the platforms, with the cobble and boulder veneer overlying much finer-grained reddish sediments (see trench photograph in Figure 3-22B). The gravel is very well-rounded, indicating considerable reworking by wave-generated currents. As pointed out before (Michel and Hayes 1991, 1993a), longshore sediment transport is clearly northwest to southeast along this pocket beach, as evidenced by the facts that: 1) there is a general decrease in grain size in that direction; 2) the berm-like ridges are oriented obliquely to the beach,

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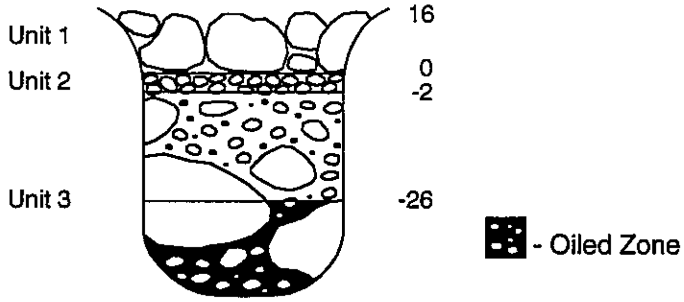
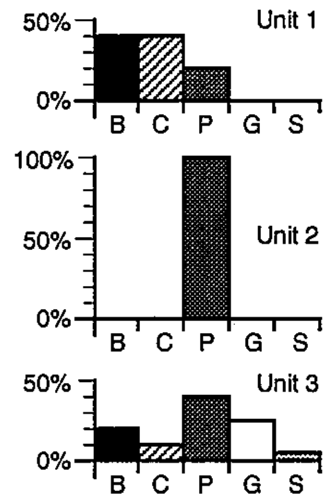
Figure 3-20. (Facing Page) Trench descriptions for station N-7 (Knight Island) on 25 July 1994. See Figure 3-17A for location of the trenches along the profile. All three trenches were located on the upper platform. Note that the top 26-30 cm of the sediments were free of oil in all trenches.

N-7 KNIGHT ISLAND, 25 JULY 1994

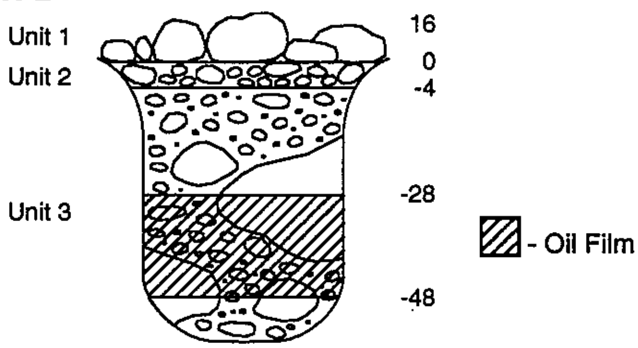
TRENCH A

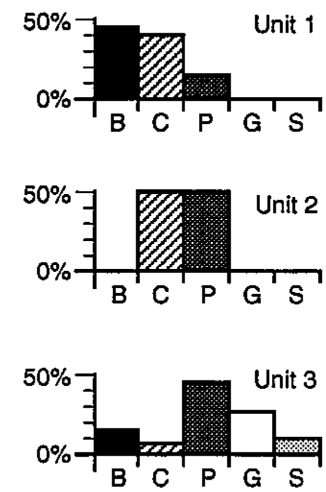




Unit 1: Clean; boulder/cobble berm face.
Unit 2: No oil; zone of pebbles below surface armor.
Unit 3: (LOR) begins at 42 cm; patch of (MOR) on top of boulder; predominantly pebbles and granules.

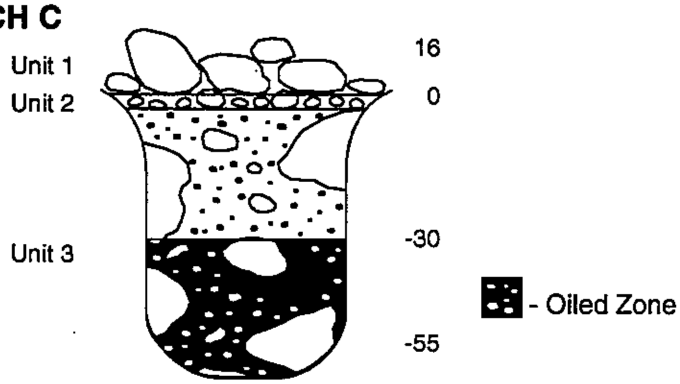
TRENCH B

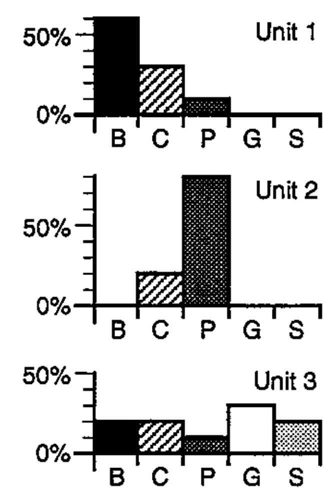




Unit 1: Clean; surface armor.
Unit 2: No oil; zone of cobbles/pebbles below surface armor.
Unit 3: (LOR), mostly rainbow sheens with patches of darker oil; uniform mix of boulders with well-packed matrix of pebbles and granules.

TRENCH C





Unit 1: Clean; boulder surface armor.
Unit 2: No oil; zone of pebbles below surface armor.
Unit 3: (MOR) 30-55 cm; (HOR) 55+ cm; not clean below.

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. A major berm-relocation project was carried out on this pocket beach, the second largest one we studied after the storm-berm relocation at Point Helen (station N-1; discussed above). Our field team visited the site on 5 September 1990 and observed the work crew making a major excavation and reworking of the sediments (about 8 m wide) down to the red soil. Although the most contaminated sediments were removed, most of the sediments removed from the excavation pit were placed on the upper platform in a zone about 25 m wide. The nature of the beach profile on that date is illustrated in Figure 3-23A. The recovery history of this beach after the berm relocation, which was quite slow, is described in detail in Michel and Hayes (1993a). A brief summary of the discussion given in that report, based on observations up through the August 1992 survey, stated that "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". However, by the time of the 23 July 1994 survey, the surface sediment grain size distribution was similar to the pattern observed before the berm relocation, except for a general coarsening of the sediment all along the profile. The armoring that originally existed on the upper platform had completely recovered.

The overlay plot in Figure 3-23A compares the beach immediately after the berm-relocation with its configuration at the time of the 23 July 1994 survey. The diagram clearly shows that the mound of sediment piled onto the upper platform had been eroded. Also, over time, much of the excavation pit had been filled in, presumably from sediment transported to the site from further to the northwest (based on the sequential surveys carried out after the excavation). Comparing the survey of 26 May 1990 and 23 July 1994, as shown in Figure 3-23B, demonstrates that the upper part of the profile has

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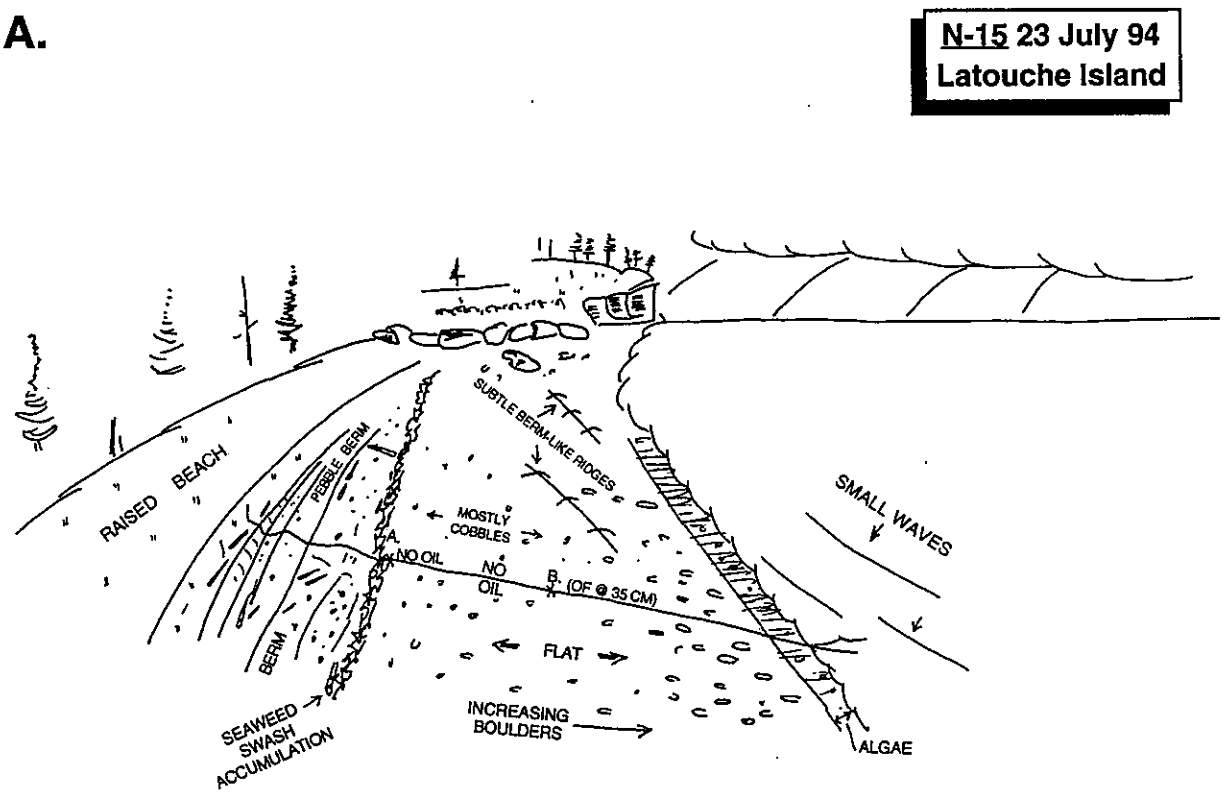
Figure 3-21. (Facing Page) Station N-15 (Latouche Island).

A. Field sketch on 23 July 1994. Note the extremely flat nature of the beach except in the area of the high-tide berms.

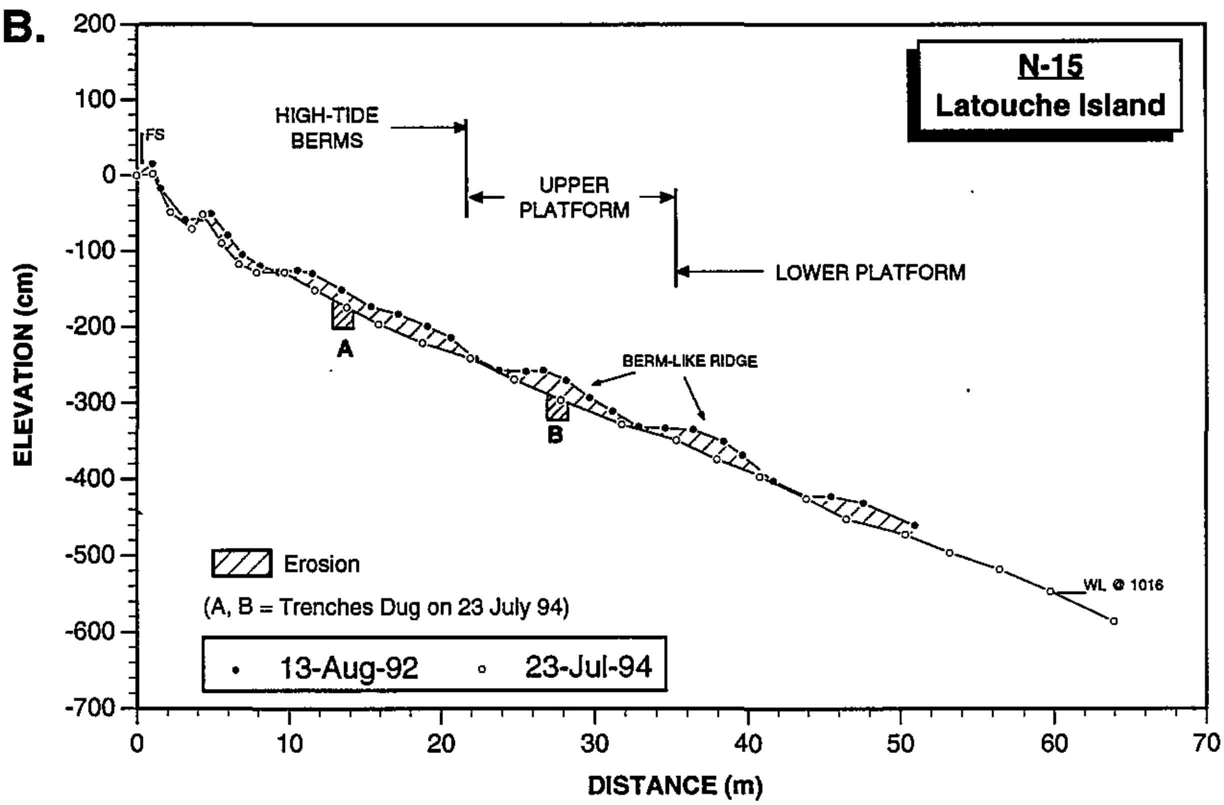
B. Comparison plots of the beach profile plotted at a 5:1 vertical exaggeration for the dates 13 August 1992 and 23 July 1994. Note that the three berm-like ridges present in 1992 were missing in 1994.

A.



N-15 23 July 94
Latouche Island
RAISED BEACH
PEBBLE BERM
BERM
SEAWEED SWASH ACCUMULATION
SUBTLE BERM-LIKE RIDGES
MOSTLY COBBLES
A. NO OIL
NO OIL
B. (OF @ 35 CM)
FLAT
INCREASING BOULDERS
SMALL WAVES
ALGAE

B.



N-15
Latouche Island
FS
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
BERM-LIKE RIDGE
A
B
Erosion
(A, B = Trenches Dug on 23 July 94)
13-Aug-92
23-Jul-94
WL @ 1016
ELEVATION (cm)
DISTANCE (m)
200
100
0
-100
-200
-300
-400
-500
-600
-700
0
10
20
30
40
50
60
70

never recovered to its pre-berm-relocation level, although some material has been added to the upper and lower platforms. This is the second station that had a berm-relocation project that has showed a net loss of sediment from the upper part of the profile four years after the berm relocation, the other one being station N-4 (Smith Island; Figure 3-13A). The berm relocation was very extensive, because of the degree and persistence of subsurface oil below the very thick and stable armor. Because this beach was among the most exposed in the Sound, it was thought that storm waves would quickly return the sediments to their original distribution. After four years, the armor did recover, but the high storm berm was still not re-built. However, as discussed below, the subsurface oil was greatly reduced.

Surface oil. This beach was heavily oiled during the spill, and much of the upper intertidal zone had a 100 percent surface cover of oil during the September 1989 survey. As shown in Table 3-1, the surface oil had been reduced to a maximum reading of 15 percent by the time of the May 1990 survey. The second highest reading of any of the exposed gravel beaches, maximum of 60 percent, was recorded at this station for the August 1991 survey. This high number was the result of the extensive berm-relocation project. Inasmuch as this is such a high-energy beach, the surface oil was mostly gone by the time of the August 1992 survey (maximum reading of 1 percent; Table 3-1). No surface oil was observed during the July 1994 survey.

Subsurface oil. Data on the subsurface oiling at this station are summarized in Table 3-5 and Figure 3-24. Most of the subsurface oil in the high-tide berms was gone before the end of the first storm season (Table 3-5). Also, the oil in the upper 20 cm or so of the upper platform sediments, which consisted of a coating on the large cobbles, was removed during the first storm season, another indication of the relatively high wave energy at this site. However, the cleaned-up cobble armor overlaid a tightly packed mixture of mostly pebbles with cobbles and granules, which was very heavily oiled,

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Figure 3-22. (Facing Page) Photographs of station N-15 (Latouche Island) on 23 July 1994.

- **A.** View looking northwest along the beach surface. Note extreme flatness of the beach, and the well-sorted surface armor.
- **B.** Trench B. An oily film was on the sediments at the bottom of the trench. Note surface armor which was finally re-established after a major berm relocation in September 1990. See Figure 3-21A for location of trench.

A.

B.

containing 10,000 to 42,000 mg/kg of oil. These heavily oiled subsurface sediments overlaid an impermeable layer of very fine-grained sediments that prevented further penetration of the sediments by the oil, which probably accounts for the high levels of oil in the subsurface sediments above the fine-grained sediments.

At the time of the 13 August 1992 survey, significant subsurface oil was found in only one trench, trench C on the upper portion of the upper platform, which was located in the swale that remained in the vicinity of the excavation pit. A sample from 10-15 cm contained 6,600 mg/kg of oil. By the time of the 23 July 1994 survey, the subsurface oil in that area had been reduced to an oil film at depths from 26 cm to at least 41 cm. A photograph of the trench in that area is given in Figure 3-22B, and it is illustrated in detail in Figure 3-25. Note the well-developed surface armor in that trench. A sample from 35-41 cm yielded a TPH value of 760 mg/kg, and the PAH level was only 0.2 mg/kg, indicating very low levels of highly weathered oil residues. Thus, the berm relocation at this station was successful in reducing the degree of subsurface oil. The surface armor had prevented any physical reworking of the subsurface sediments, and the oil had concentrated in a zone on top of the impermeable subsoil. This oil would surely have persisted as an asphalt pavement for many years without excavation of the most heavily oiled sediments, tilling to break up the residual oil, and sediment relocation to speed reworking of the oiled sediment.

Station N-17 (Perry Island)

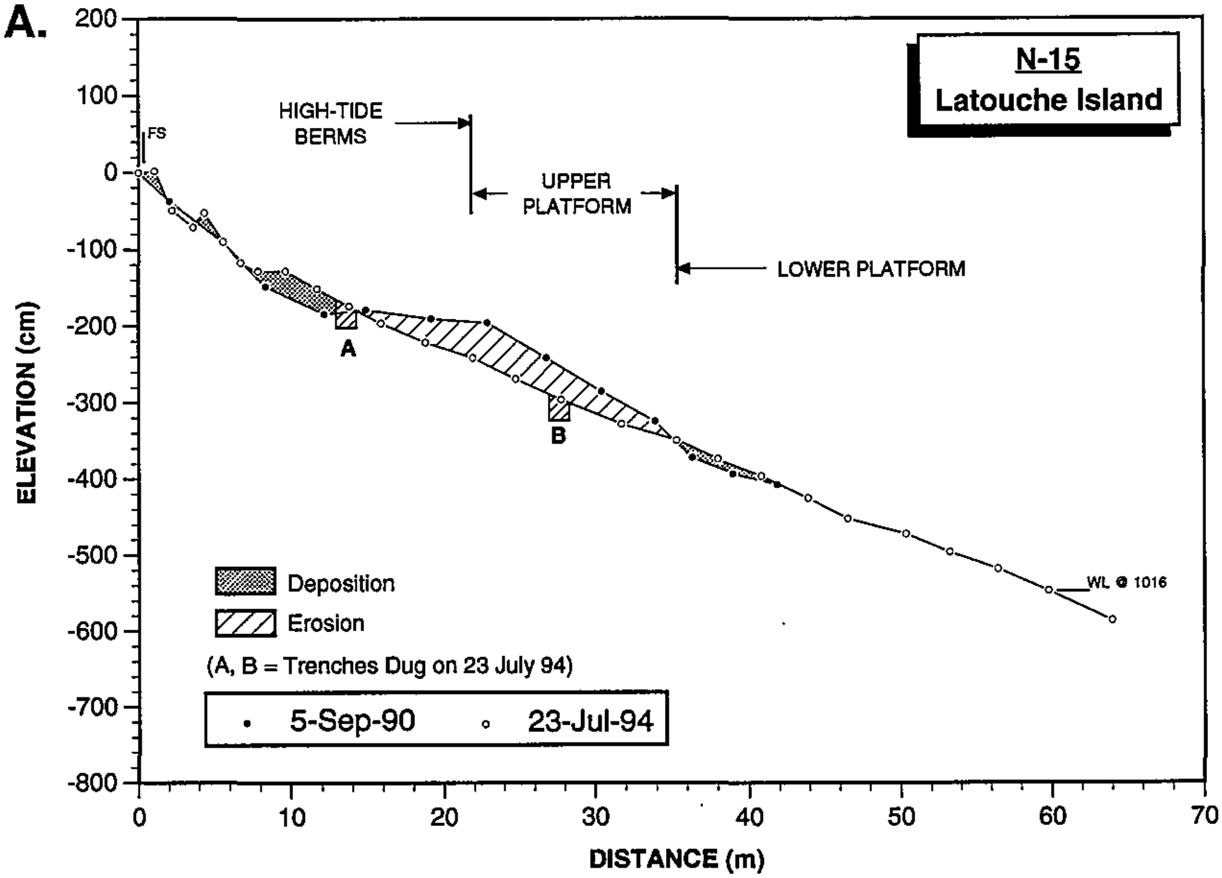
Introduction. This station, which is located on a small east-facing pocket beach near the south end of Perry Island (Figure 1.1), has a long easterly fetch, and, consequently, experiences considerable wave action. The beach is similar sedimentologically and geomorphologically to the other stations classified as cobble/boulder platforms with berms. The field survey of 26 July 1990, the ninth visit to the site, revealed little that had not already been reported in our summary of the 1992 survey (Michel and Hayes 1993a).

Figure 3-23. **(Facing Page)** Comparison beach profile plots for station N-15 (Latouche Island) plotted at a 5:1 vertical exaggeration.

A. Surveys on 5 September 1990, taken just after the berm relocation, and the latest survey, 23 July 1994, illustrating the ultimate loss of much of the sediment excavated during the berm-relocation project.

B. Surveys on 26 May 1990 (prior to berm relocation) and 23 July 1994, which shows a net loss of sediment in the high-tide berm area, and gain on the platforms over the four year period.

A.


N-15
Latouche Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
FS
A
B
WL @ 1016
Deposition
Erosion
(A, B = Trenches Dug on 23 July 94)
5-Sep-90
23-Jul-94
ELEVATION (cm)
DISTANCE (m)
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0
10
20
30
40
50
60
70

B.

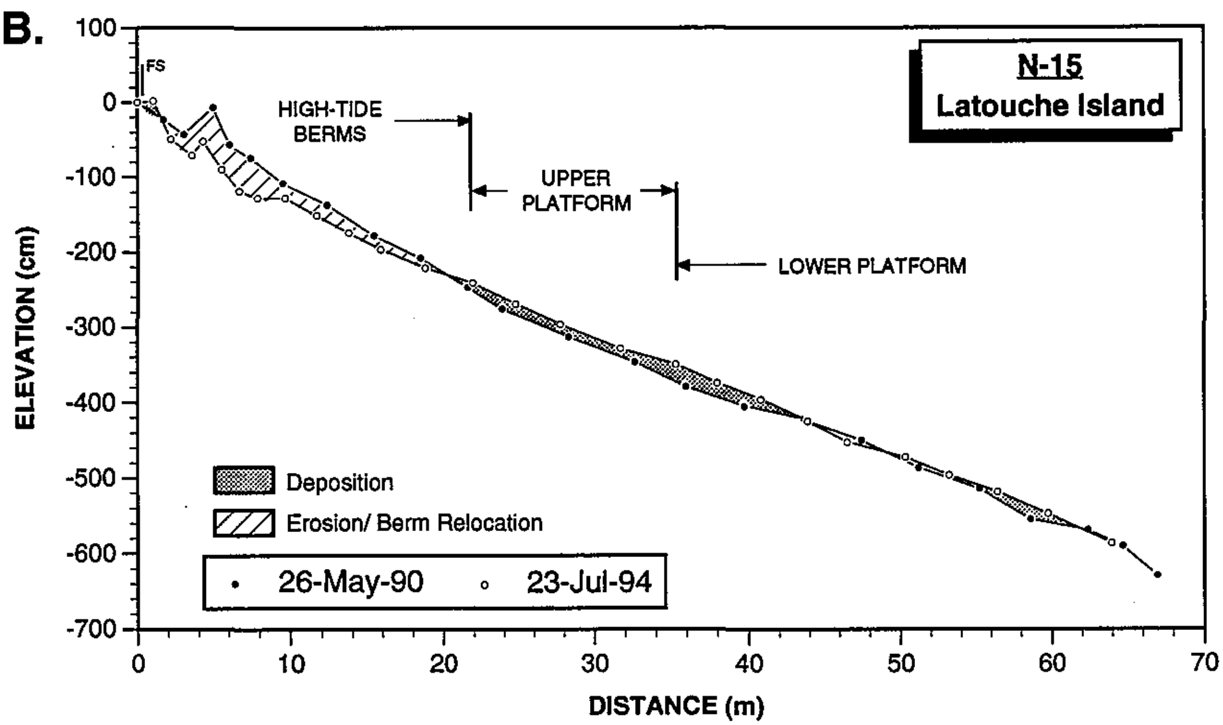

N-15
Latouche Island
HIGH-TIDE BERMS
UPPER PLATFORM
LOWER PLATFORM
FS
Deposition
Erosion/ Berm Relocation
26-May-90
23-Jul-94
ELEVATION (cm)
DISTANCE (m)
100
0
-100
-200
-300
-400
-500
-600
-700
0
10
20
30
40
50
60
70

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)	
July 1994	No oil	26-41+ (OF)	

The oiling history of the site was relatively brief. Although a maximum reading of 70 percent surface oiling was recorded during the September 1989 survey, the surface sediments were completely free of oil at the end of the first storm season (Table 3-1). However, there was enough subsurface oil at the site to justify a berm-relocation project at the end of the summer of 1990. During the December 1989 survey, subsurface sediments were lightly oiled to 45 cm and 30 cm in the high-tide berms and upper platform, respectively. The site was not surveyed in the summer of 1990 because of an eagle nest nearby, thus the station was not revisited until after the berm-relocation project was completed. The berm-relocation project was restricted to the high-tide berm area, where the sediments were composed of uniformly sized pebbles and small cobbles.

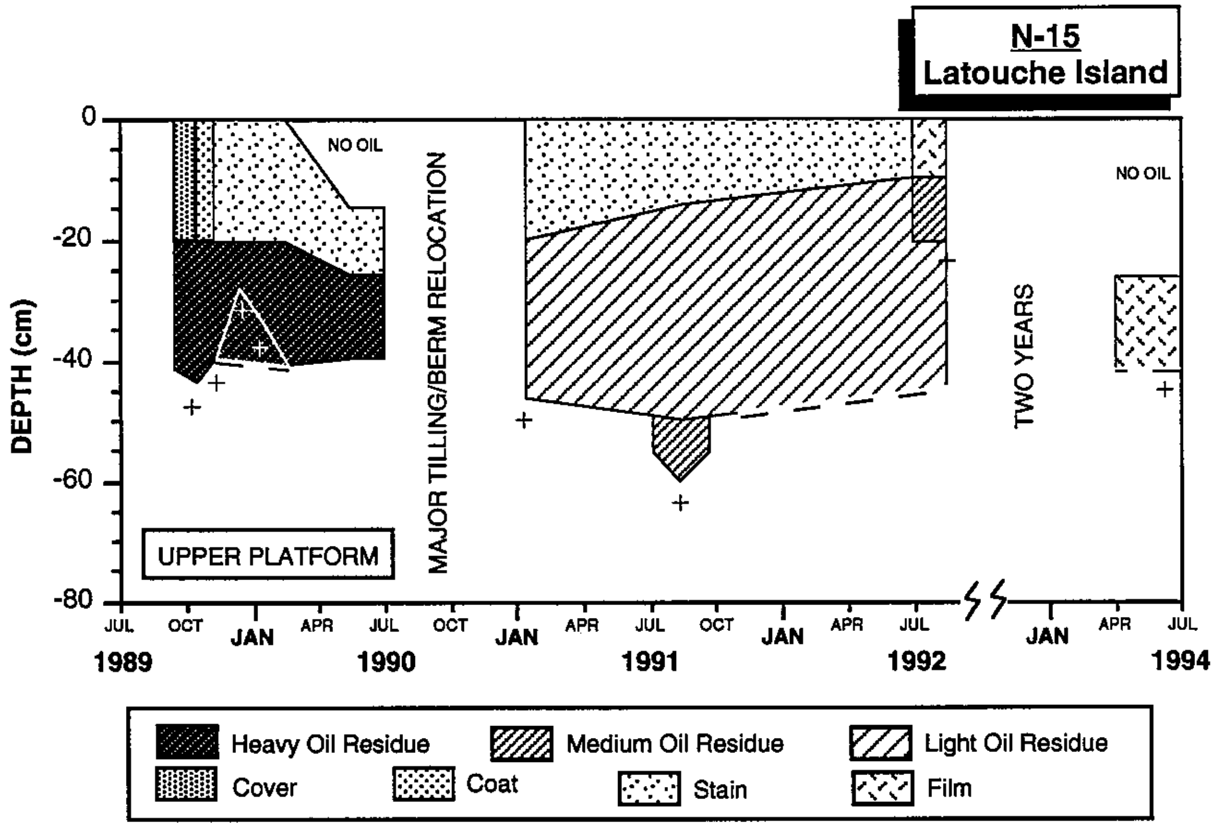


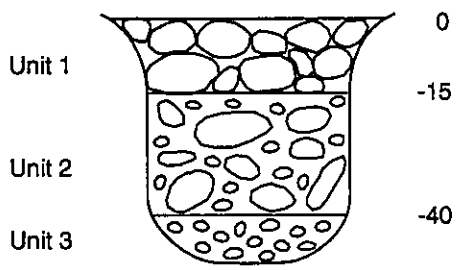
Figure 3-24. Time-series plot of the interval and degree of subsurface oiling at station N-15 (Latouche Island), for the period September 1989 through July 1994. The major tilling/excavation in September 1990 greatly reduced the oil concentration in the upper platform. Without this physical removal and breakup of the heavy oil layer below the armor, it is likely that an asphalt pavement would have formed and persisted for a very long time.

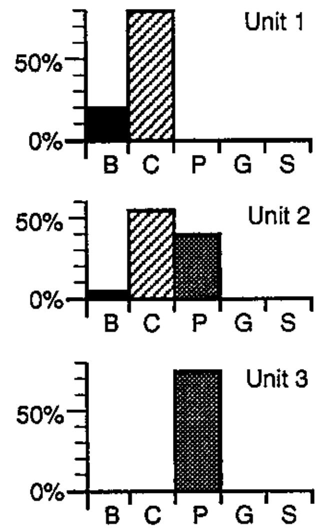
By the end of the 1990-1991 storm season, there was no oil in the subsurface sediments of the high-tide berms, only light oily films were present on the subsurface sediments of the upper platform, and the beach had been restored to its original morphology and sediment distribution patterns. The beach sediments were essentially oil free during both the 1992 and 1994 surveys. A sample of 34-45 cm from the upper beachface had a TPH value of 50 mg/kg and PAH of 0.2 mg/kg. These levels are essentially background for these measurements. Michel and Hayes (1993a) listed the following important factors that have contributed to the steady and complete removal of oil from the subsurface sediments of this beach:

1) The steady flow of groundwater from a freshwater lagoon perched behind the beach;
2) The relatively steep slope of the platform (6 degrees);

N-15 LATOUCHE ISLAND, 23 JULY 1994

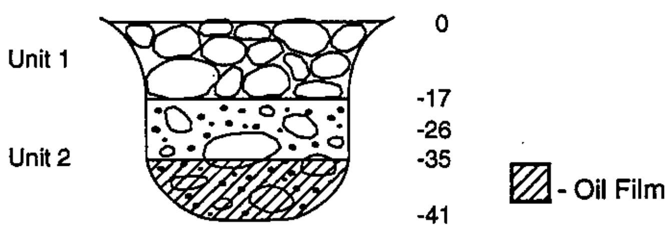
TRENCH A

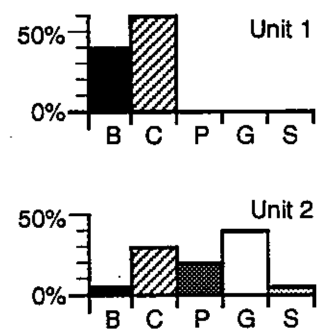




Unit 1: No oil; well-developed cobble armor.
Unit 2: An organic mushy material was present.
Unit 3: Sediments were red, with soft peaty material.

TRENCH B





Unit 1: No oil; well-developed cobble armor.
Unit 2: Thin silver sheens on the water table at 26 cm.

Figure 3-25. Trench descriptions for station N-15 (Latouche Island) on 23 July 1994. Oiled sediments only occurred in trench B. Note excellent armoring of the surface sediments in trench B. See Figure 3-21A for location of trenches.

3) The very uniform grain size of the gravel in the beach, consisting almost entirely (95 to 100 percent) of pebbles and cobbles in the oiled zone.

4) The absence of a fine-grained component of sand and granules under the coarse-gravel armor and on the rock platform. Without such a fine-grained component, the oil had a much smaller surface area on which to adhere, and the permeability of the sediments was greatly enhanced, improving the effectiveness of groundwater and tidal flushing.

BAYHEAD BEACHES

Introduction

Two of the stations studied, N-18 (Sleepy Bay) and N-14 (Northwest Bay), are located at the apex of moderately large bays (Figure 1.1) and are classified here as bayhead gravel beaches. Both of these stations have streams that flow across the beach near the permanent profile, and the switching of the stream mouths has had a major influence on the long-term changes of the beaches. These gravel beaches differ from those classified as cobble/boulder platforms with berms in the following ways: 1) the grain size of the gravel is smaller, being composed mostly of pebbles and small cobbles; 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) streams that have formed minor deltas on the beach occur near the profile.

Station N-18 (Sleepy Bay)

Introduction. Located at the very south end of Sleepy Bay (Figure 1.1), this station is the site of significant wave action on occasion, as evidenced by the way the beach has changed over time. The large waves that do occasionally impact the beach are presumably the result of its northerly orientation and a northeasterly fetch of 25 km. The stream at the head of the bay is the site of a run of pink salmon each year.

As noted by Michel and Hayes (1993a), Sleepy Bay was one of the most heavily oiled areas of Prince William Sound during the spill, probably because its shape trapped most of the oil that entered it. Large amounts of oil penetrated the pebble berms to depths of more than 50 cm. In fact, oil penetrated the stream banks to the west of the profile to depths greater than 125 cm, as found by excavations with a backhoe in 1989. Consequently, this beach became an area of considerable concern during the spill response because of the difficulty of removing the subsurface oil, particularly with the pink salmon spawning beds being nearby.

Morphology and sediments. As illustrated by the field sketch and beach profiles in Figure 3-26, the beach at station N-18 consists of an area of high-tide berms composed mostly of pebbles that changes frequently over time, a very stable central ramp, and migrating low-tide bars in the lower intertidal zone. A view from the high-tide line that looks offshore down the profile is given in the photograph in Figure 3-27A.

Most of the significant morphological changes noted at this beach during our twelve surveys can be related to two activities: 1) the migration of the stream mouth and its associated delta; and 2) a major excavation of the subsurface oiled sediments at the site that took place in the summer of 1991. During the cleanup of the subsurface oil, several piles of the dug-up, boulder-sized rubble were left on the beach, and two of the piles were on the survey line at station N-18 (see photograph in Figure 3-27B).

The rather spectacular changes over time at this relatively sheltered gravel beach are summarized in Figure 3-28. At the time of the May 1990 survey, the beach appeared to be in a slightly erosional mode, particularly in the lower section, but the surface sediment was relatively clean, with a maximum surface oil reading of 5 percent. When the site was revisited in 22 January 1991, however, the clean surface sediments had been eroded and large patches of heavily oiled sediments that were formerly in the subsurface were then exposed on the surface. The reason for this change was that the mouth of the stream had migrated 50 m to the east and the stream channel had cut across the profile. This change of the stream position apparently brought about the erosion of the beach surface and the resulting exposure of the formerly subsurface oiled sediments. The erosion probably was the result of the stream sweeping the middle part of the beach clean of pebbles at different stages of the tide. As shown by the January 1991 sketch in Figure 3-28, a long spit/bar crossed the profile offshore of the stream channel.

By the time of the field survey of 28 August 1991, the beach excavation had occurred and the stream channel had switched back to the west. As a result of a combination of the mounding of excavated rubble (and assorted other sediment) on the beach and a highly modified intertidal bar having welded to the mid-section of the profile, the beach had gained a considerable amount of sediment since the January 1991 survey. It is assumed that when the stream shifted west, probably abruptly during a period of high runoff of the stream, the abandoned end of the spit/bar that was across the lower part of the profile in January had migrated further up the beach by August.

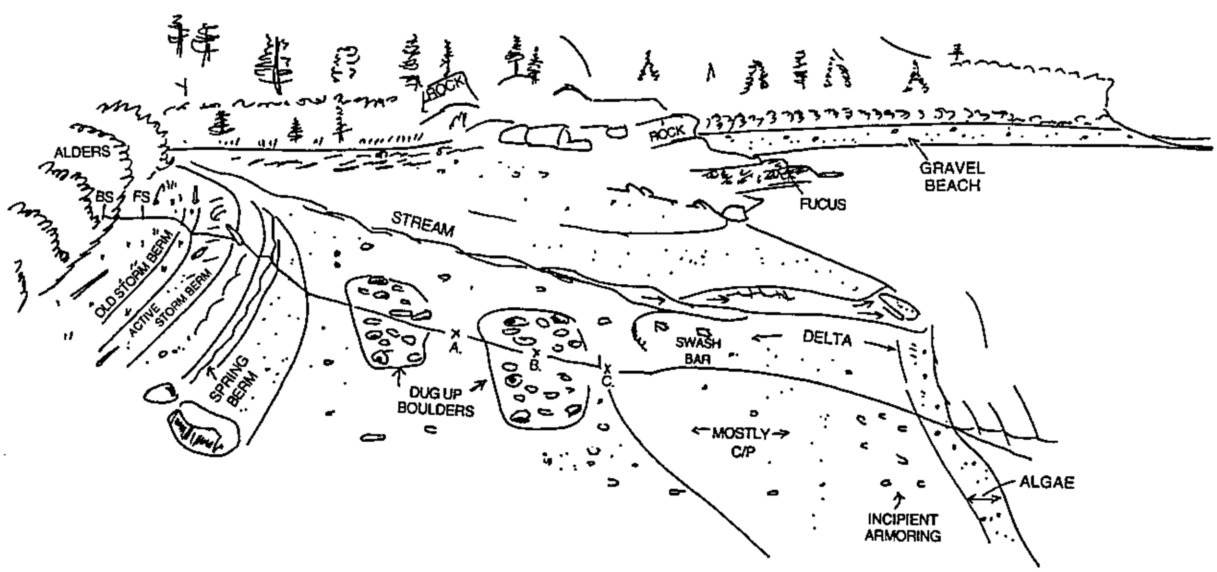
Figure 3-26. (Facing Page) Station N-18 at the head of Sleepy Bay.

A. Field sketch on 22 July 1994. Note the two residual patches of boulder-sized rubble that were excavated from the underlying slope during the beach-excavation project of the summer of 1991. The sediment deposition is the result of the old stream delta welding onto the beach after the stream channel switched to the west.

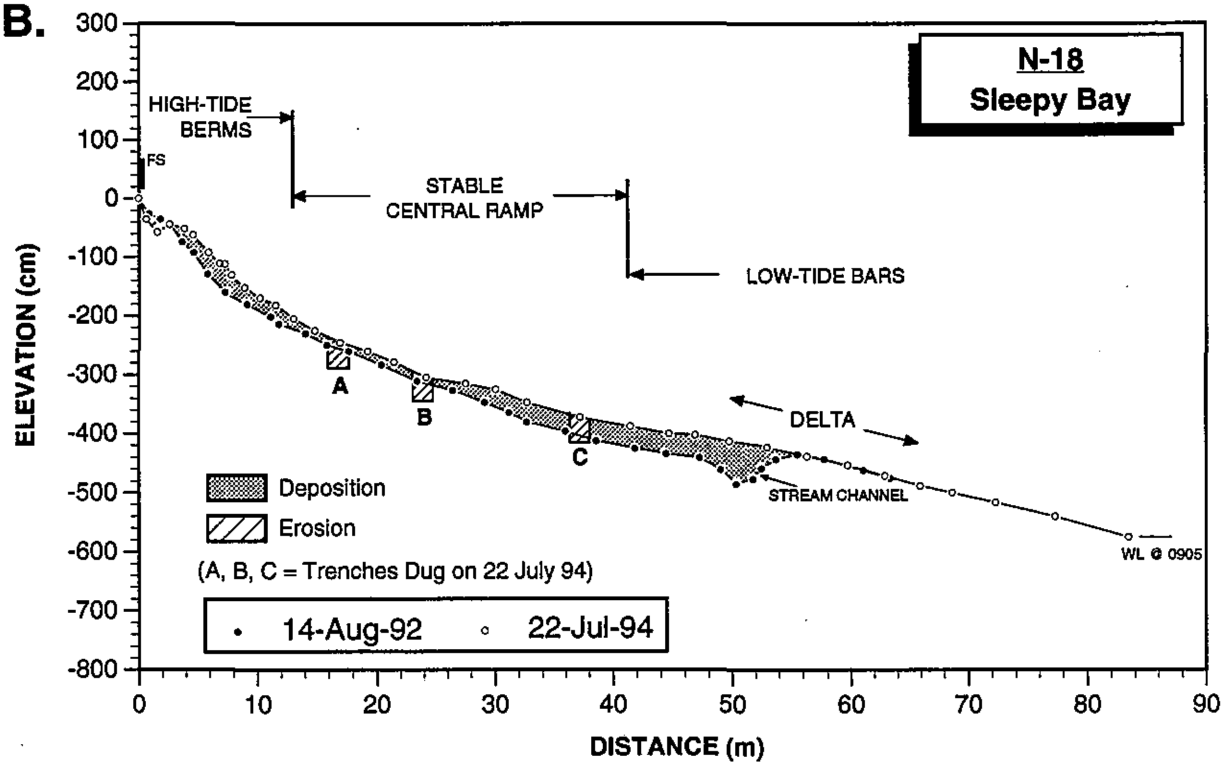
B. Comparison of the 14 August 1992 and 22 July 1994 surveys, plotted at a 5:1 vertical exaggeration. The beach was highly depositional in July 1994 in comparison with August 1992.

A.

N-18 22 July 94
Sleepy Bay



B.



When we returned to Sleepy Bay on 14 August 1992, the stream had once again migrated to the east and across the profile. The sediment that had accumulated on the beach in the summer of 1991 had been eroded away and the surface of the beach had returned to near its January 1991 level. Again, a well-developed spit/bar was located on the seaward side of the stream channel. Although the mounded excavated sediment had been lowered to the original level of the profile, the angular rubble remained in place such that one could still discern the location of the original rubble 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. Nonetheless, the resilience shown by this beach to recover its original topography after such extreme modification is remarkable. Of course, the switching of the stream mouth to the east probably speeded up the process.

At the time of the 22 July 1994 survey, the stream mouth was once again located to the west of the profile (see field sketch and profiles in Figure 3-26). The beach was depositional throughout in comparison with the 14 August 1992 survey, no doubt because of the landward migration of the stream delta as a result of an abrupt shift of the stream mouth to the west. We do not know if this happened more than once in the two-year interval that separated the two surveys. This type of pattern probably would occur on most bayhead, fine-gravel beaches with stream outlets, a very common type of beach on the coastline of western North America.

Despite the remarkable recovery of the beach profile surface after the excavation project, the sediment distribution pattern still reflects the presence of the excavated coarse, boulder-sized rubble (see comparison sediment grain size plots in Figure 3-29). A photograph of the residual coarse rubble is given in Figure 3-27B.

Surface and subsurface oiling. Over the first storm season, the maximum surface oil readings dropped from 100 percent in September 1989 to five percent in May 1990. Estimates of up to 50 percent stain were made for the excavated sediment piles in August 1991, but it was all cleaned up during the ensuing storm season (see Table 3-1).

Figure 3-27. (Facing Page) Photographs of station N-18 (Sleepy Bay) on 22 July 1994.

- **A.** View down profile from the high-tide line. Arrow points to location where photograph B was taken. The field team members are digging trenches B and C.
- **B.** Residual rubble-slope boulders dug from under beach during the oiled sediment excavation project carried out during the summer of 1991.

A.

B.

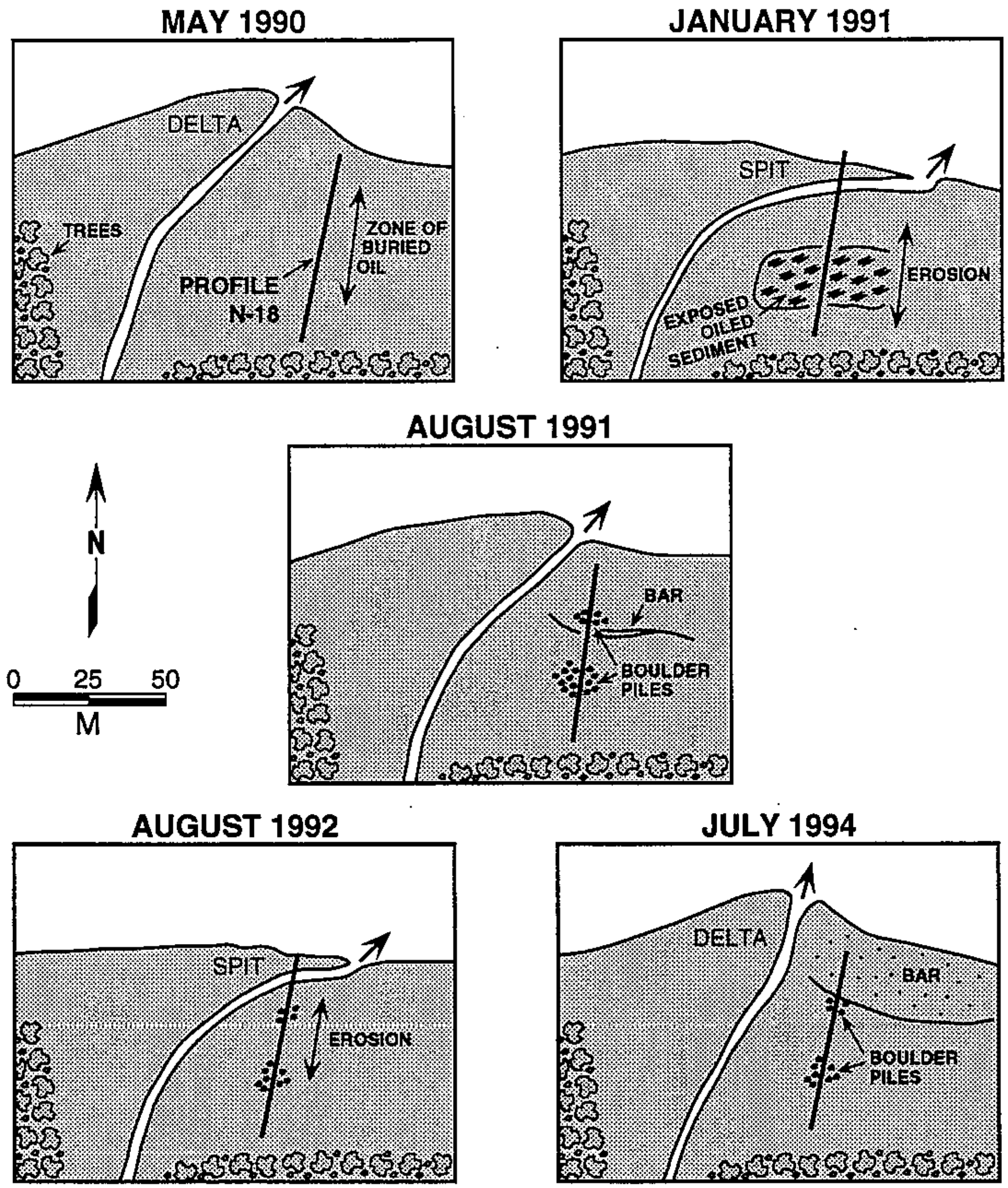


Figure 3-28. Relation of changes in beach morphology to changes in the position of the stream outlet at station N-18 (Sleepy Bay) between May 1990 and July 1994.

No surface oil was on the beach during either the August 1992 or the July 1994 survey. Subsurface oiling at the head of Sleepy Bay remained a serious problem until the massive excavation/manual removal project was carried out in the summer of 1991. Observations on this troublesome subsurface oil are reported in detail by Michel and Hayes (1993a). For example, all five of the trenches dug on the profile 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.

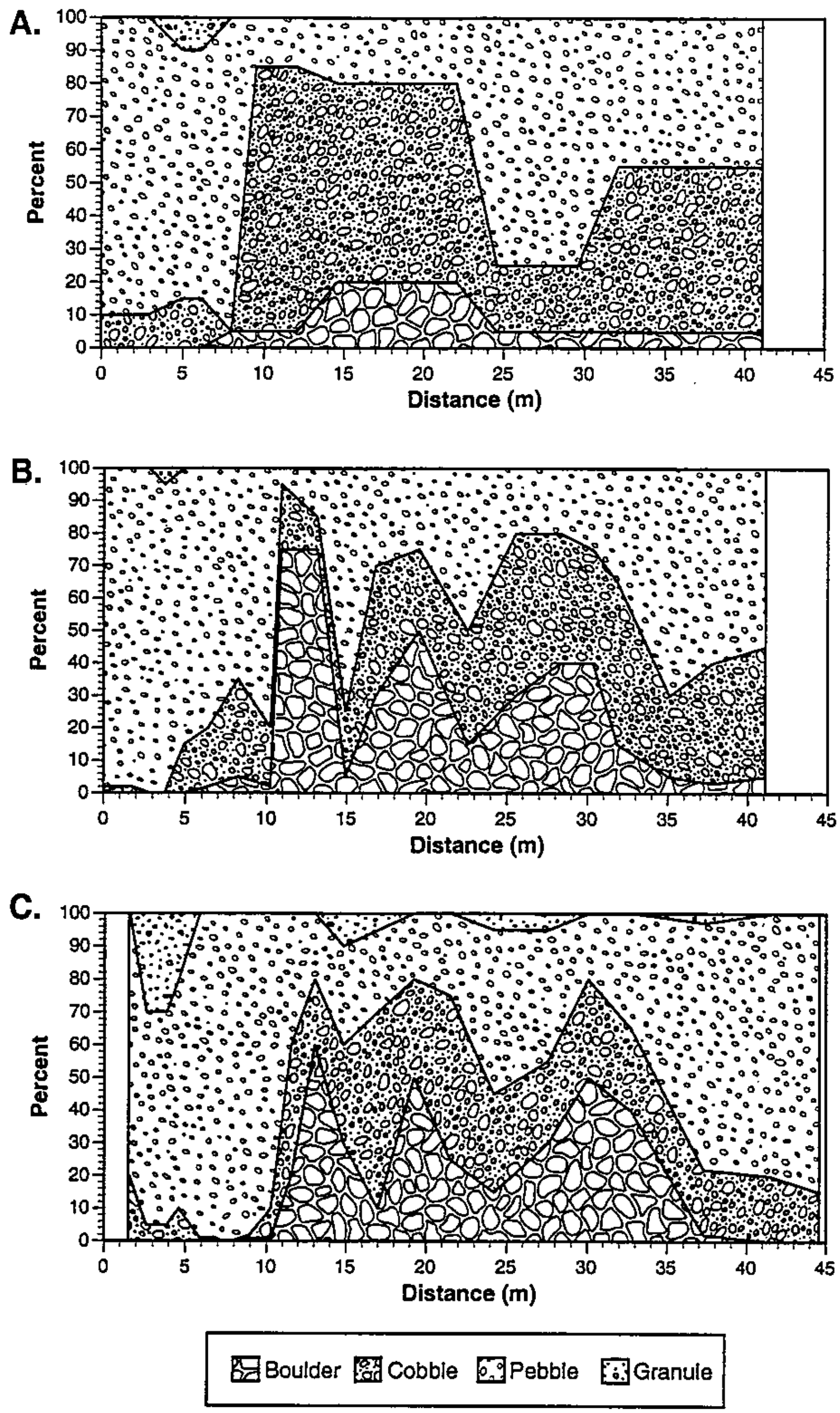


Figure 3-29. Comparison of surface sediment distribution patterns for station N-18 (Sleepy Bay) on: (A) 26 May 1990; (B) 14 August 1992; and (C) 22 July 1994. The increase in the boulder content in the middle of the profile in the 1992 and 1994 surveys was the result of a major beach excavation project carried out on this beach in the summer of 1991. Apparently, waves at this site do not generate currents with sufficient competency to transport these large boulders.

By the time of the 1992 survey, there was no visible oil in any trenches dug at the station, and no samples were collected. During the 1994 survey, again, no oil was observed in the trenches, and no samples were collected.

Station N-14 (Northwest Bay)

This station, which has been surveyed nine times to date, is located at the head of the west arm of Northwest Bay on Eleanor Island (Figure 1-1). Wave action is probably low-to-moderate during storms because of the narrow entrance and the length of the bay. However, even moderate waves can generate currents strong enough to move the relatively fine gravel of this beach (more than 50 percent pebbles with considerable intermixed granules).

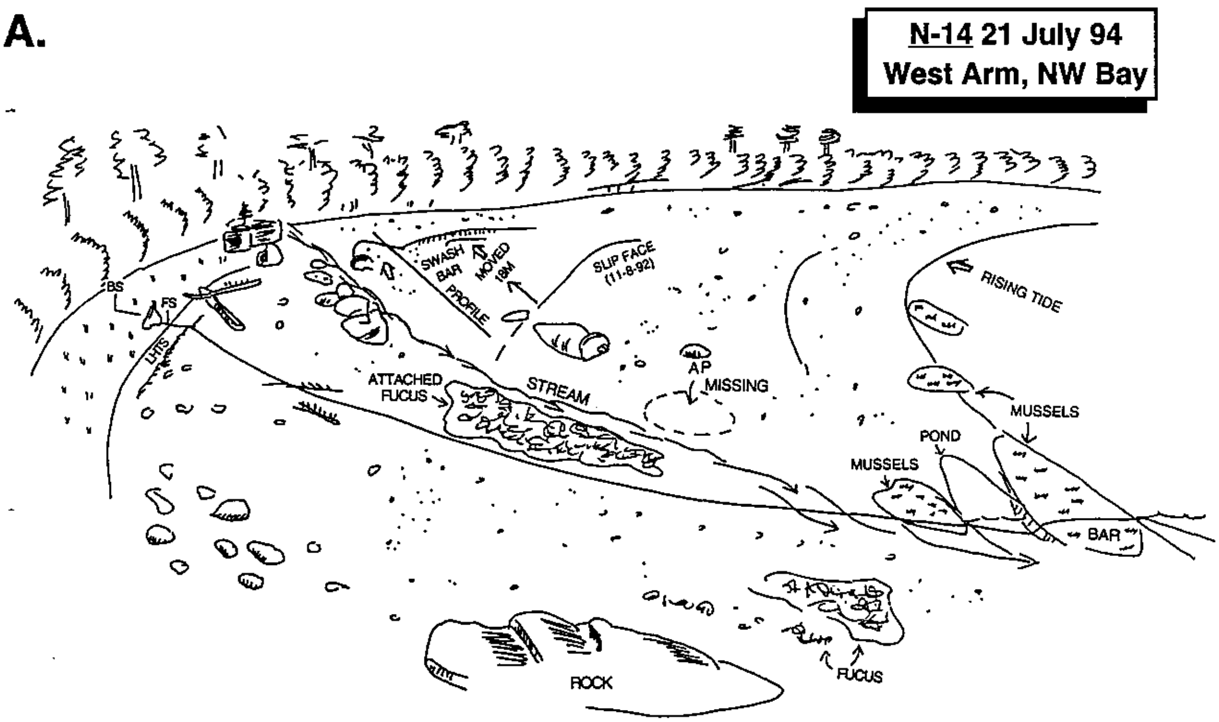
This beach was free of surface oil by the time of the May 1990 survey and of subsurface oil by February 1990, even though it was heavily oiled during the spill. As pointed out by Michel and Hayes (1991), this beach was treated thoroughly during the 1989 cleanup effort. There was extensive flushing of oiled sediment into the lower intertidal and subtidal zone during the 1989 washing activities. Whereas the hydraulic flushing was an efficient way to clean this fine-grained and relatively hard-packed beach, the biological monitoring studies being conducted by NOAA at this site suggest that the hydraulic flushing had the following negative effects on the biota: 1) direct mortality of organisms; 2) reduced growth rates; and 3) 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).

Figure 3-30. (Facing Page) Station N-14 (Northwest Bay).

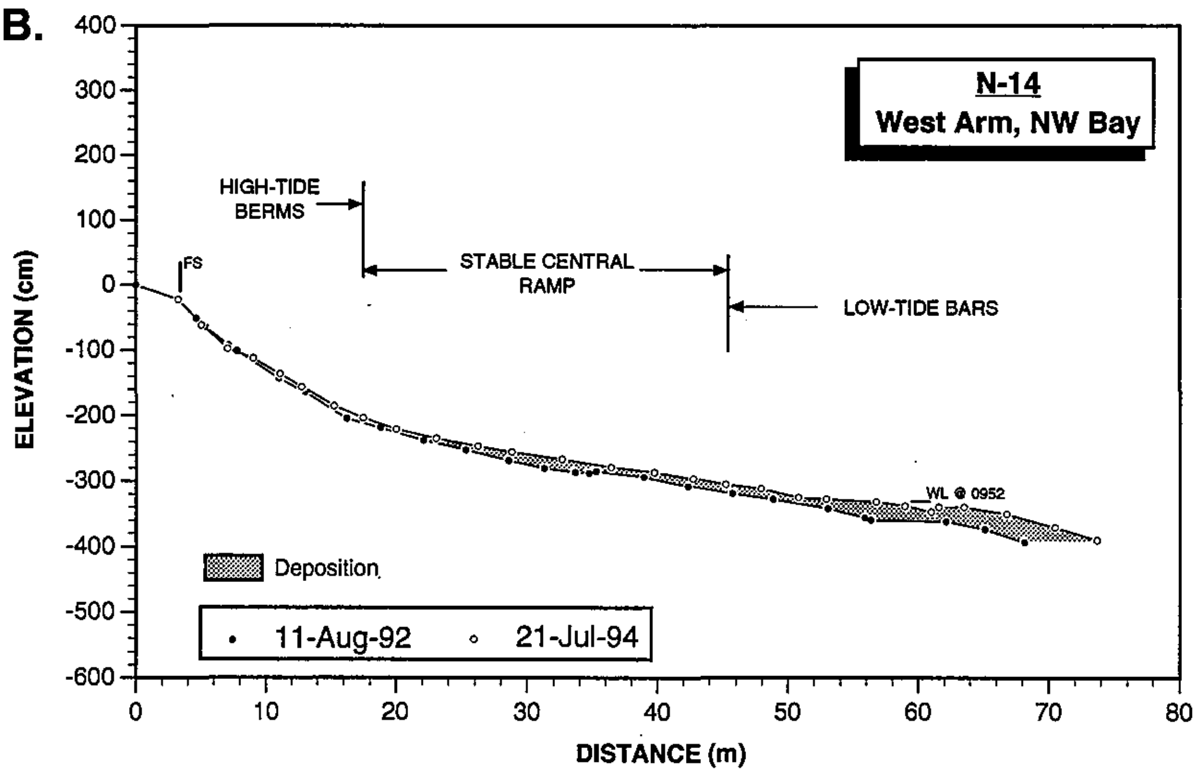
A. Field sketch made on 21 July 1994. Note that the intertidal bar on the far (west) side of the stream had migrated another 18 m landward since the 1992 survey. The surficial asphalt pavement on the other side of the stream that was present in the lower intertidal zone during the 1992 survey was missing, presumably eroded away by wave or stream-current action.

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

A.


N-14 21 July 94
West Arm, NW Bay
BS
FS
LHTS
SWASH BAR
PROFILE
MOVED 18M
SLIP FACE (11-8-92)
RISING TIDE
ATTACHED FUCUS
STREAM
AP
MISSING
MUSSELS
POND
MUSSELS
BAR
ROCK
FUCUS

B.


N-14
West Arm, NW Bay
HIGH-TIDE BERMS
STABLE CENTRAL RAMP
LOW-TIDE BARS
FS
WL @ 0952
Deposition
11-Aug-92
21-Jul-94
ELEVATION (cm)
DISTANCE (m)
400
300
200
100
0
-100
-200
-300
-400
-500
-600
0
10
20
30
40
50
60
70
80

As far as the beach morphology is concerned, our data show a slow, but continued, return of sediments to the beach since the hydraulic flushing occurred. Our surveys also show that the overall level of the beach was raised between 50 and 75 cm during the interval between 24 January 1991 and 11 August 1992. As the intertidal swash bar across the stream to the west from the profile migrated landward, a formerly buried zone of asphalt pavement was exposed to the surface. This same bar had migrated another 18 m up the profile by the time of the 21 July 1994 survey (see field sketch in Figure 3-30A),and the asphalt had been removed, apparently by natural processes. A profile run across the swash bar and a photograph of it are presented in Figure 3-31. As shown in the comparison plot of beach profiles given in Figure 3-30B, the overall level of the beach along the profile was elevated even further during the time interval between the 11 August 1992 and 21 July 1994 surveys. This may be indirect evidence that there was a considerable amount of sediment washed from this beach during the cleaning process, and, after five years, all of the displaced sediment had not yet returned to the upper beach.

PEBBLE BEACH/TIDAL FLATS

Introduction

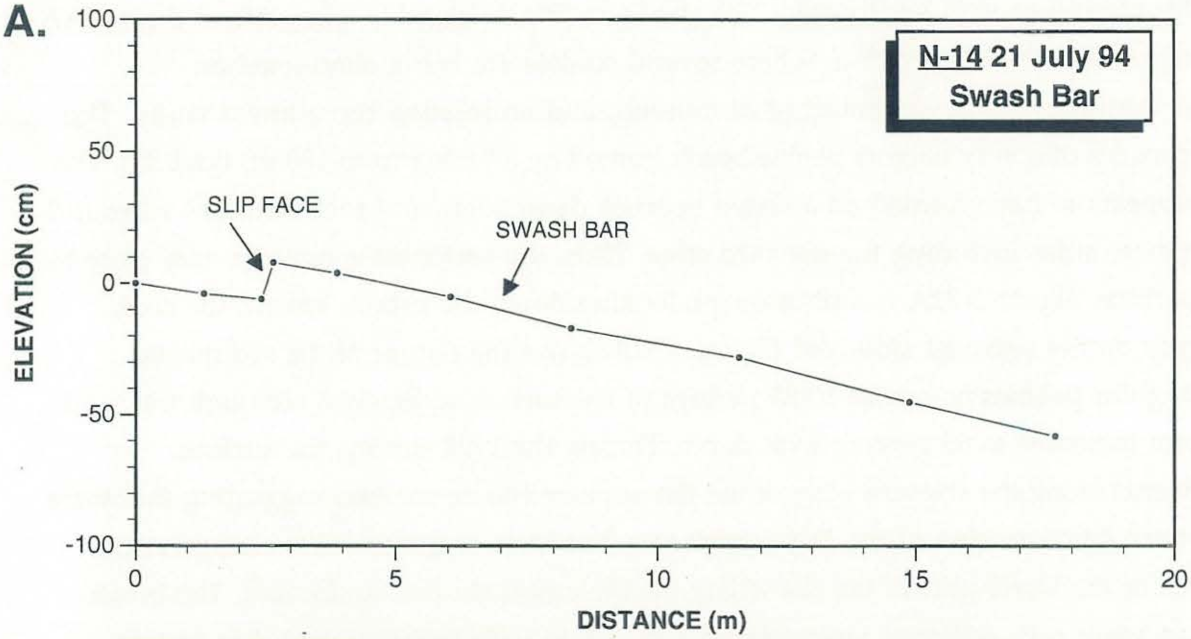
Exposed tidal flats are rare in Prince William Sound, comprising only 0.1 percent (2.6 km) of the shoreline, and they are even rarer in the part of the Sound affected by the *Exxon Valdez* oil spill. The flats are composed of sand to small pebbles, and they are often backed by a pebble beach, indicating exposure to some wave action. There is usually peat below the shallow sediments. These habitats can host a rich biological community. At the two NOAA stations on tidal flats, N-9 on Block Island and N-11 on Crafton Island, clams are present in the intertidal area and eelgrass beds are common in adjacent subtidal areas. Both stations were surveyed in July 1994.

Figure 3-31. (Facing Page) Intertidal swash bar at station N-14 (Northwest Bay) on 21 July 1994.

A. Topographic profile of the bar plotted at a 5:1 vertical exaggeration. The line of the survey is given on the field sketch in Figure 3-30A.

B. Photograph of bar.

A.


N-14 21 July 94
Swash Bar
ELEVATION (cm)
DISTANCE (m)
SLIP FACE
SWASH BAR
100
50
0
-50
-100
0
5
10
15
20

B.

Station N-9 (Block Island)

Morphology and sediments. The station on Block Island is a key site in the NOAA biological monitoring program where several studies are being conducted on transplanting of clams, monitoring of mussels, and an infauna recruitment study. The site consists of a very narrow pebble beach fronted by a wide (up to 100 m) tidal flat. The flat appears to have formed on a raised bedrock depression, and rock outcrops surround it on three sides including the seaward edge. Thus, the water table remains very close to the surface. Figure 3-32A is a photograph looking down the profile toward the rock outcrop on the seaward side, and Figure 3-32B shows the nature of the sediments. Subangular pebbles comprise 60-85 percent of the surface sediments, although the sand content increases to 65 percent with depth. During the 1994 survey, the surface sediments along the western edge of the flat appeared to be coarser, suggesting that there had been some erosion of the finer sediments, but there was no visible change in the profile or the lower part of the flat where the biological studies are located. The beach and adjacent rock outcrops were treated extensively with high-pressure, hot-water flushing techniques in 1989; manual removal and nutrient addition were conducted in 1990.

Surface and subsurface oil. There has been essentially no visible surface oil at this station since June 1990, although in 1992 we were able to find some small residues by carefully searching in the surrounding rocky area where asphalt pavements had been removed. Often where there is a high water table and wet sediments, oil does not readily adhere to the substrate. However, the heavy oil loading at this site eventually led to oil penetration and contamination of the subsurface sediments, particularly along the lower part of the tidal flat where the rock outcrops shelter the sediments from both waves and currents. The oil did not penetrate into the underlying peat, which appeared to remain water saturated.

Figure 3-32. (Facing Page) Photographs of station N-9 (Block Island) on 21 July 1994.

A. View down the profile of the tidal flat from the pebble beach. Note the coarseness of the surface sediments and the rock outcrops that surround the tidal flat. Person in yellow is at Trench A; Trench B is indicated by arrow.

B. Trench B, showing the silver sheens that accumulated on the water table. Note the angularity of the surface pebbles and the high sand fraction below the surface. The sediments were described as OF (indicating contamination with oil films).

A.

B.

The degree of contamination of the sediments has varied widely, with TPH measurements in samples collected along the profile going up and down by an order of magnitude over time and space. In August 1992, black oil droplets were visible in trenches along the profile. Two years later, in July 1994, only small stringers of silver sheen were visible on the water filling two of the trenches in the middle part of the flat. Figure 3-32B shows the oil sheens on the high water table in Trench B, located about mid-flat. Note the subangular pebbles that cover the surface. A sample from this trench at 2-10 cm contained 80 mg/kg TPH and only 0.2 mg/kg PAH, reflecting the very low levels of oil remaining in the middle of the tidal flat. These results are the lowest measured for samples described as containing oil. However, it should be noted that much higher levels of contamination are present lower on the flat away from the profile line, and the NOAA biological monitoring team considers this site to be the most contaminated of all their sites.

Station N-11 (Crafton Island)

Morphology and sediments. This site is located in a small, circular embayment on the west side of Crafton Island (Figure 1-1). It is sheltered from wave activity by headlands on both sides of the entrance to the embayment, thus, there has been no change in the beach profile over the last five years. The surface is covered with angular pebbles, which overlay peaty sand. The water table is very high, perched on the peaty substrate. This station was surveyed for the twelfth time in July 1994.

Surface and subsurface oil. No oil was observed on the surface sediments in either 1992 or 1994. However, the extent and degree of subsurface oil has been difficult to quantify visually. The water table is high, the sediments are dark and peaty, and natural, organic sheens can form on the water in trenches. Sample results have documented that the upper intertidal zone was heavily contaminated in patches. Under a clean surface layer of pebbles there were greasy zones containing TPH levels of 10,900 mg/kg in August 1992 and 2,100 mg/kg in July 1994 (see Trench A in Figure 3-33A). In contrast, oil

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Figure 3-33. (Facing Page) Photographs of station N-11 (Crafton Island) on 20 July 1994.

A. Trench A, located at the high-tide line, showing the tightly packed, angular surface pebbles overlying a zone of moderately oiled residue (MOR). A sample from 0-10 cm contained 2,100 mg/kg TPH. When dug deeper, the trench quickly filled with water.

B. Trench B, located 2.5 m down slope from Trench A. The only visible oil was a thin silver sheen on the water table.

A.

B.

was never found in the lower intertidal flat. This segment was not treated with flushing techniques, only manual removal and fertilizer treatments, thus there was no potential for transport of oiled sediments into the lower zone during cleanup. This site provides a good comparison with N-9 on Block Island where extensive flushing occurred and the lower flat sediments remain contaminated five years later. We concluded after the 1992 survey that, where the lower intertidal zone is relatively flat and contains fine-grained sediments, there is considerable risk of contamination of the tidal flat sediments from high-volume flushing of the upper parts of the shoreline. This concern still holds true five years post-spill.

SHELTERED ROCKY COASTS

Many parts of Prince William Sound affected by the *Exxon Valdez* oil spill are characterized as sheltered rocky coasts, that is, a narrow bedrock cliff or ledge that contains little or no surface sediments. Oil heavily coated the entire bedrock surface initially, but persisted mostly on the upper intertidal zone, above the heavy *Fucus* cover. Over the first year, at least 50 percent of the surface oil was removed (Michel et al. 1991). By two years later, only trace amounts of oil remained on bedrock surfaces. However, sheltered rocky coasts had three persistent types of oil residues: 1) oil associated with sediment accumulations on the bedrock, such as tombolos; 2) oil trapped in crevices and under a thin sediment veneer on the rock surface; and 3) very patchy coating of oil remaining on the sides and undersides of large rock outcrops.

Station N-6 in Bay of Isles (Figure 1-1) is a typical sheltered rocky shore, with a thin veneer of sediment formed by in-place weathering of the bedrock (Figure 3-34A). The station is located on the eastern end of a set-aside segment, thus no cleanup was conducted in 1989. There is some confusion as to whether manual removal was conducted in 1990 or 1991. During the July 1994 survey, there was a trace amount of oil

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Figure 3-34. (Facing Page) Photographs of station N-6 (Bay of Isles) on 23 July 1994.

A. View across the profile showing the surface covered with sediments derived from in-place weathering of bedrock. The arrow points to the location of Trench B.

B. Trench B, showing the asphalt pavement formed in the sediment-filled crevices on the bedrock. Note the lighter, clean silty sediments below the darker, oiled sediments. This site was set-aside and not treated in 1989.

A.

B.

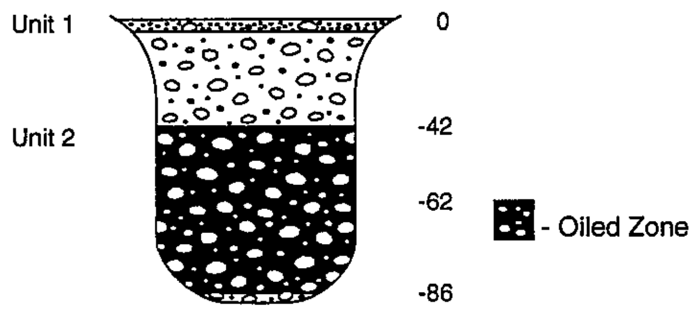
coat on the sides of the bedrock outcrops. This distribution was similar to that observed during the 1992 survey. Most of the oil residues were in the form of asphalt pavements, which covered 3-5 percent of the surface over a width of 9.5 m of the upper intertidal zone. These pavements were located in sediment-filled crevices on the bedrock surface. The oil penetrated the more permeable surface sediments, to a depth of about 10 cm, to where the substrate become silty and impermeable (see photograph in Figure 3-34B). These pavements contain large amounts of oil, with TPH levels of 35,700 and 27,300 mg/kg for the top 5 cm of sediment from trenches A and B, respectively, the highest TPH levels of all samples collected in 1994. Total PAH were also high, at 230 and 150 mg/kg. Below a hardened surface crust, the oiled sediments were soft and the oil medium brown in contrast to the black surface oil. Once such pavements are formed in these highly sheltered areas, they are extremely persistent. The scattered patches of pavement at station N-6 are expected to persist for tens of years. However, the oil is extremely immobile and not likely to be released to the environment. Continued weathering and hardening of the surface crust are expected to decrease the likelihood of release.

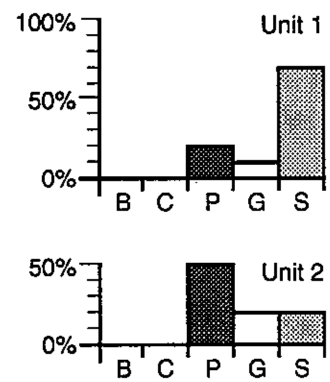
The profile at station N-10 in Herring Bay (Figure 1-1) runs down a gully between two massive bedrock outcrops. There are patches of rounded pebbles in the bedrock crevices, and a pebble pocket beach perched at the high-tide line, indicating that this area is exposed to some wave action when winds are from the west. In 1991, the maximum percent surface cover of oil was 10 percent, in 1992 it was 5 percent, and as of July 1994 only 1-2 percent coat and asphalt pavements remained. The width of the oiled zone decreased by about 25 percent over the period between 1992 and 1994. Some of the oil coat on the landward sides of the outcrop had a heavy coat of spruce needles, which has been noticed at this site during every survey since 1990. The persistence of spruce needles adhered to the oil coat reflects the high degree of sheltering of these underrock surfaces.

Just north of the rock outcrop at station N-10 is a well-developed pebble beach where in May 1990 our team discovered a deeply buried oiled pebble layer. In July 1994, the depth to the oiled layer in a trench located in the lower intertidal zone was 26 cm (compared to 22 cm in 1992), and clean sediments were reached at a depth of 63 cm, thus the oiled layer was 37 cm thick (Figure 3-35B). Chemical analysis of a sample from 35-52 cm showed the sediments contained 470 mg/kg TPH and 13 mg/kg PAHs (Table 2-2). The TPH level was relatively low because the oil occurred as a thin coating on individual clasts rather than filling the pore spaces. In a trench at the high-tide line, the

N-10 HERRING BAY, 25 JULY 1994

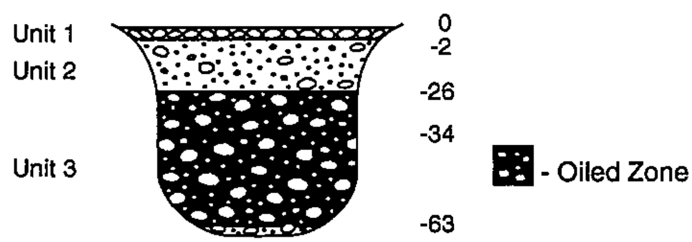
TRENCH @ HIGH-TIDE LEVEL

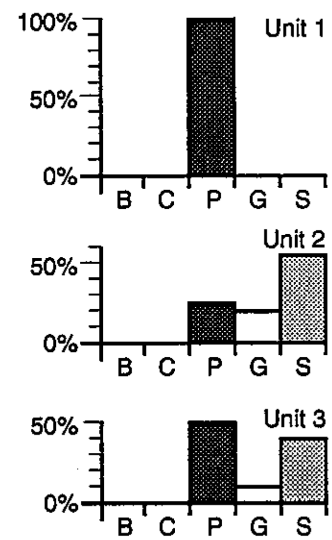




Unit 1: Clean.
Unit 2: (LOR) from 42-62 cm; sediments coated with brown, organic-rich clay with black oil droplets. (MOR) from 62-86 cm; similar but darker in color. Clean below.

TRENCH @ LOWER INTERTIDAL ZONE





Unit 1: No oil; pebble layer; 2 cm thick.
Unit 2: Clean zone, abundant sand.
Unit 3: Top ±10 cm of oil was light brown, soft like mousse; from 34-63 cm, oil was black, sediment coated with organic-rich clay. Oil readily sheened on water table. Clean below.

Figure 3-35. Descriptions of two trenches in the pebble beach north of station N-10. Note the persistence of both oil and an organic-rich clay at depths of 26 and 42 cm below the surface.

oiled sediments began at 42 cm and clean sediments were reached at 86 cm (Figure 3-35A). The oil formed a thick brown sheen when the trench was flooded by the rising tide, appearing unchanged from that observed in 1992 and shown in Figure 3-38 in Michel and Hayes (1993). The oil at this site was among the least weathered of all samples collected in 1994 (see discussion in Chapter 5). This deep oil layer most likely represents the remains of oil which originally penetrated to these depths and has not yet been removed by natural processes. It is surprising that the oil had persisted more than five years, because the well-rounded and well-sorted pebbles are readily reworked by storm waves and high flushing rates would be expected in such well-sorted and permeable sediments. However, it is obvious that the sediments are not reworked to depths greater than 26-42 cm because of the persistence of the oil and the organic clay coating on the clasts. This site may be unique in that the deeply penetrated oil is still present in the lower intertidal zone.

ROCKY RUBBLE SLOPES

Introduction

Much of the shoreline along the bays of Knight Island is composed of an odd combination of a rocky rubble upper intertidal zone and a zone of finer sediments in the lower intertidal zone, characterized as a raised bay bottom (uplifted by the 1964 earthquake). The rocky rubble slopes are bedrock which is overlain by a poorly sorted mix of sediments which have accumulated there under the influence of gravity. These sediments range in size from large boulders to clay, and the gravel clasts are angular, indicating that they have not undergone reworking or sorting by wave action. The topographic profiles do not change over time. The rubble sediments also range widely in their degree of permeability, as does the depth to which oil penetrated the substrate. Natural removal processes are limited to tidal flushing, biodegradation, and photo-oxidation. Two stations, N-5 and N-13 (both were set-asides), are located on this shoreline type.

Station N-5 (Snug Harbor)

The profile N-5 in Snug Harbor (Figure 1-1) has been surveyed ten times, the last survey being conducted on 25 August 1991. The rocky rubble is composed of large boulders (Figure 3-36A), and oil residues in 1994 consisted of 1-5 percent coverage of oil in crevices between the boulders in a band less than 2 m wide. The patches of oil were very small, occurring where angular pebbles were packed in finer sediments. Figure 3-36B shows the oil coating on the buried tips of pebbles pulled from the crevices. Below the surface, the oil was very soft and mousse-like, indicating that it has undergone limited weathering. Total PAH were 330 mg/kg, relatively high for the TPH level of 32,500 mg/kg.

Station N-13 (Herring Bay)

General Description

This station was also a set-aside where no cleanup was conducted. It is located deep inside Herring Bay (Figure 1-1), with effectively no fetch perpendicular to the beach, and thus it is well sheltered from wave action. The beach typifies the rocky rubble slope (Figure 3-37A), with angular boulders and cobbles overlying a poorly sorted substrate (Figure 3-37B). The lower half of the beach is a raised bay bottom, covered by pebbles with dense barnacle growth and mussel beds. This site has been visited during each NOAA survey, for a total of fourteen times.

Oiling History

Since there was no cleanup in 1989, surface oil coverages of 80-100 percent were recorded along the upper 10 m during the September 1989 survey. By summer 1990, oil coverage had decreased by 50 percent, and by summer 1991, it was no more than 10 percent. The surface oil did not gradually thin. Instead, it appeared to be thicker than at treated sites, and removal occurred as the oil dried, hardened, and flaked off. No surface oil has been observed since 1991.

In trenches dug into the rubble slope, the degree of subsurface oiling has been highly variable, reflecting the preferential penetration into the more permeable zones along contacts between the rubble and the finer-grained matrix. Sediments collected in September 1989 at a depth of 43 cm contained 47,000 mg/kg TPH, whereas subsequent samples ranged from <10 to 7,700 mg/kg. Since 1991, samples of oil described as MOR from depths of 15-25 cm have consistently contained 3,750-7,700 mg/kg TPH and 15-1,120 mg/kg PAHs, a relatively narrow range for the TPH measurement considering the inherent variability in collecting a sample from a substrate as variable as shown in Figure 3-37B. The subsurface oil continued to generate black oil droplets on the water table in both trenches as of July 1994. It had undergone intermediate weathering (see

Chapter 5 for discussion), showing little change since 1992. In the upper trench (shown in Figure 3-37B), clean sediments were reached at 25 cm below the surface, which does not include the 20 cm of surface rubble.

It should be noted that oil penetration to such depths was not found to be widespread along rubble slopes, based on spring shoreline surveys (known as SCAT surveys) conducted by the authors in 1990 and 1991. Also, the extent of subsurface oiling at the site quickly dropped off to the north, as the shoreline transitioned to rubble on top of bedrock rather than on a sediment substrate. It is likely that, in the absence of efforts to remove the heavy surface oil accumulations at this set-aside site, the surface oil eventually penetrated into the sediment substrate during the summer of 1989. Lower oil accumulations, more viscous oils, or a less-permeable sediment substrate would not have caused such extensive subsurface oiling. The permeability of the substrate at N-13 is exemplified by the high water table and large amount of groundwater flow observed in trenches during each survey.

This deep penetration, persistence, and relatively slow weathering rate of subsurface oil in this shoreline type has led us to add a second type of sheltered rocky shore to the shoreline ranking system used for Environmental Sensitivity Index (ESI) mapping: sheltered rubble slopes. These shoreline types should receive higher priority for protection and cleanup because of the higher risk of oil penetration into the more permeable substrate, compared to sheltered bedrock shores where impermeable bedrock limits the depth of oil penetration. Removal of heavy surface oil by flooding or washing techniques <u>before</u> it has a chance to penetrate into the substrate should be considered.

Figure 3-36. (Facing Page) Photographs of station N-5 (Snug Harbor) on 22 July 1994.

A. View across the profile showing the rocky rubble surface (where the two persons are standing) and the pebble/cobble surface of the raised bay bottom. Oil residues of 1-5 percent cover of asphalt pavements remained in the rubble zone as of 1994.

B. Close-up of a patch of asphalt pavement. Note the oil on the edges of the angular pebbles pulled from between the crevices in the lower center of the photograph (arrow points to oil). Below the surface crust, the oil is brown, soft, and mousse-like.

A.

B.

Figure 3-37. (Facing Page) Photographs of station N-13 (Herring Bay) on 21 July 1994.

A. View of the upper intertidal zone showing the rocky rubble slope. The profile begins where the log extends from the vegetation. Note the coarseness of the surface rubble, compared to the sediment substrate below the rubble, shown in the lower photograph.

B. Trench A, showing poorly sorted sediment substrate. Oil penetrated from 0-25 cm, and clean sediments were reached below. Note the greasy look and wetness of the sediments and the black oil droplets on the water table. A sample from 15-25 cm depth contained 3,800 mg/kg TPH and 45 mg/kg PAHs.

A.

B.

CHAPTER 4
A TECHNIQUE FOR CALCULATING AN EXPOSURE INDEX FOR SHORELINES OF PRINCE WILLIAM SOUND

INTRODUCTION

The importance of the level of exposure of a field site to hydrodynamic forces is one of the time-honored concepts in both oil-spill response and ecological studies. Usually, the primary focus is on wave-energy flux, as it is in this discussion, although currents generated by tides and winds are important in some situations. Heavy wave action is the single most effective natural process for cleaning shorelines of spilled oil.

Unfortunately, wave-energy flux is quite site-specific, and sophisticated wave gauges that measure wave conditions through several seasons are required for a precise understanding of wave conditions at any coastal site. Engineering firms sometimes do this kind of monitoring before designing certain coastal engineering structures. But, at most oil spill sites, one will be faced with the fact that essentially no statistically valid wave data will be available, which was the situation in Prince William Sound.

In the absence of wave gauges, engineers commonly hindcast wave conditions based primarily on seasonal wind data, ship-board wave observations, information on swell conditions, and nearshore bathymetry. Hindcasting works best for open ocean shorelines where seasonal conditions are fairly uniform and well understood. Hindcasting was not attempted for Prince William Sound because, of the information needed, only the bathymetry is known in the detail required. Also, the costs involved relative to anticipated meaningful results were thought (by us) to be prohibitive. The wind regime of the Sound is very complex, and each site would require a separate hindcast.

On the other hand, one can usefully apply the concept of exposure level in a general way to oil-spill sites, as is done in the Environmental Sensitivity Index (ESI), whereby the most exposed shorelines (e.g., exposed rocky coasts; ESI = 1) are projected to have little or no oil persistence and the most sheltered coasts (e.g., salt marshes; ESI = 10) have the greatest potential for long-term impact. In fact, the concept of exposure level was an inherent component of the project design and execution of both the geomorphological/ chemical NOAA study (Michel and Hayes 1991) and of the biological study (Lees et al. 1991) of the *Exxon Valdez* spill site.

Using geomorphic indicators, such as size and roundness of sediments, size of beach berms, and presence of storm berms, the geomorphological sites studied during this project are believed to have the following ranking with regard to exposure to wave action (highest to lowest):

cobble/boulder platforms with berms

↓

bayhead beaches

↓

pebble beach/tidal flats

↓

rocky rubble slopes and sheltered rocky shores

The locations of the geomorphology/chemistry stations are given in Figure 1-1 and their classification is listed in Table 4-1.

Also using general geomorphological criteria, plus well-understood biological adaptations, such as mode of attachment and feeding patterns, the biological sites were noted to be exposed or sheltered (Lees et al. 1991). The sites designated as exposed boulder/cobble (B-CO) were thought to be subject to considerable wave action and those termed protected rock (RKY) and protected mixed-soft (MS) were not. The locations of the biological stations are shown in Figure 4-1 and their biological class is listed in Table 4-2. Note that the classification in Table 4-2 is shown for the upper, middle, and lower intertidal zone.

The purpose of this chapter is to summarize our best estimate of the exposure levels in Prince William Sound without the benefit of detailed wave-gauge records or mathematical model studies. After considerable thought and research, we have concluded that a good approximation of the relative wave-energy flux at the specific study sites in Prince William Sound could be obtained by relating wind duration and velocity to the effective fetches (straight line distance over which wind blows to create the waves) at each site. Three years of field studies in Prince William Sound have shown that wind conditions are highly variable throughout the Sound on an hour-by-hour basis. No specific long-term wind data are available for the different locations in the Sound, although NOAA established wind recorders on Lonetree, Seal, and Danger Islands (Figure 1-1) for the non-summer months of 1989/1990. We have complete daily wind data for these three sites for the period 22 November 1989 to 6 March 1990. This is the best, and in fact the only, data we have on the details of wind conditions in the Sound after the spill. These data are presented in Figures 4-2, 4-3, and 4-4.

Table 4-1. Exposure index for geomorphology stations.

Station	Geomorphologic Class	Wind Rose Used	Exposure Index
N-17 (Perry Island)	Cobble/Boulder Platform with Berms	Lonetree	1,021
N-4 (Smith Island)	Cobble/Boulder Platform with Berms	Seal Island	881
N-15 (LaTouche Island)	Cobble/Boulder Platform	Seal Island	790
N-3 (Smith Island)	Cobble/Boulder Platform with Berms	Seal Island	730
N-1 (Point Helen)	Cobble/Boulder Platform	Seal Island	648
N-18 (Sleepy Bay)	Bayhead Beaches	Seal Island	506
N-7 (Knight Island)	Cobble/Boulder Platform with Berms	Seal Island	357
N-10 (Herring Bay)	Sheltered Rocky Shores/ Moderately Exposed Gravel Beaches	Lonetree	173
N-14 (Northwest Bay)	Bayhead Beaches	Lonetree	64
N-6 (Bay of Isles)	Sheltered Rocky Shores	Seal Island	31
N-11 (Crafton Island)	Pebble Beaches with Tidal Flats	Lonetree	20
N-12 (Crafton Island)	Rocky Rubble Slopes	Lonetree	20
N-5 (Snug Harbor)	Rocky Rubble Slopes	Seal Island	14
N-9 (Block Island)	Pebble Beaches with Tidal Flats	Lonetree	10
N-13 (Herring Bay)	Rocky Rubble Slopes	Lonetree	8

Note: Original NOAA stations N-2, N-8, and N-16 were discontinued and therefore were not included in this analysis.

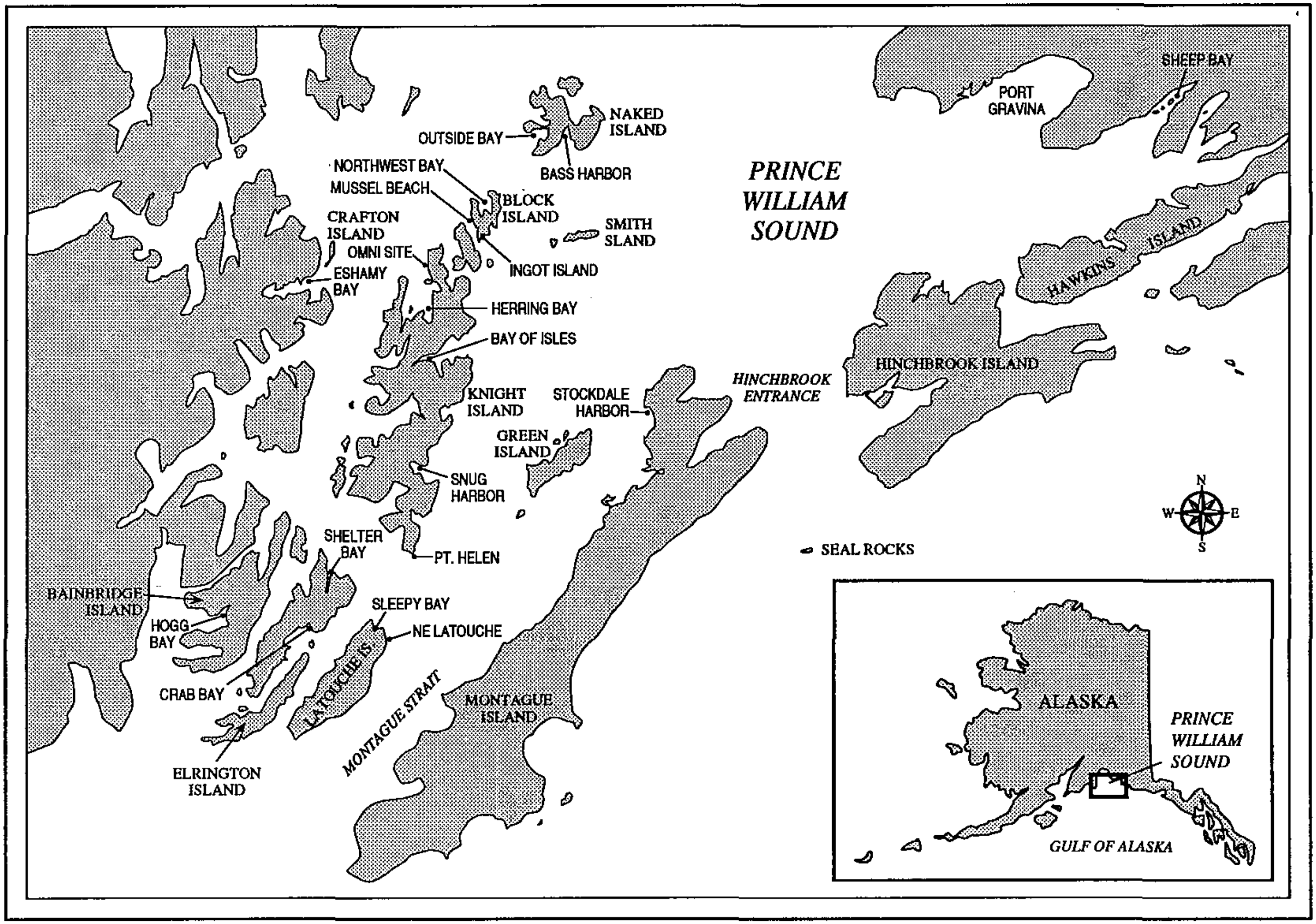


Figure 4-1. Location of biological monitoring sites in Prince William Sound (after Lees et al. 1991).

Table 4-2. Exposure index for biology stations.

Station (GEO STA)	Biology Class (U/M/L)	Wind Rose Used	Exposure Index
Northeast Latouche Island (N-15)	—/B-CO/B-CO	Seal Island	790
Smith Island (N-3)	B-CO/B-CO/B-CO	Seal Island	730
Point Helen (N-1)	—/B-CO/B-CO	Seal Island	648
Sleepy Bay (N-18)	—/MS/MS	Seal Island	506
Elrington Island	RKY/RKY & MS/MS	Seal Island	234
Ingot Island	—/B-CO/MS	Lonetree	205
Bass Harbor	RKY/B-CO/B-CO	Seal Island	176
Outside Bay	RKY/RKY/RKY	Lonetree	173
Herring Bay (Omni Barge [N-10])	B-CO/B-CO/B-CO	Lonetree	173
Northwest Bay West Arm (N-14)	—/MS/MS	Lonetree	64
Mussel Beach	RKY/MS/MS	Lonetree	52
Outside Bay-Site 1	MS/MS/MS	Lonetree	28
Hogg Bay	RKY/RKY/RKY	Danger Island	27
Crafton Island (N-11; N-12)	MS/MS/MS	Lonetree	20
Sheep Bay	MS/MS/MS	Seal Island	15
Snug Harbor (N-5)	RKY & MS/RKY & MS/ RKY & MS	Seal Island	14
Crab Bay	MS/RKY & MS/RKY & MS	Seal Island	14
Block Island (N-9)	MS/RKY/MS	Lonetree	10
Bay of Isles (N-6)	MS/RKY/MS	Seal Island	8
Herring Bay (N-13)	RKY & MS/RKY/MS	Lonetree	8
Eshamy Bay	RKY/RKY/RKY	Lonetree	7*
Shelter Bay	—/MS/MS	Seal Island	6
Northwest Bay Islet	RKY/RKY/RKY	Lonetree	3

* This exposure index is assuming a south-facing shore, relatively sheltered from the east. East-facing shores on the north side of the entrance to Eshamy Bay have considerably higher exposure index values.

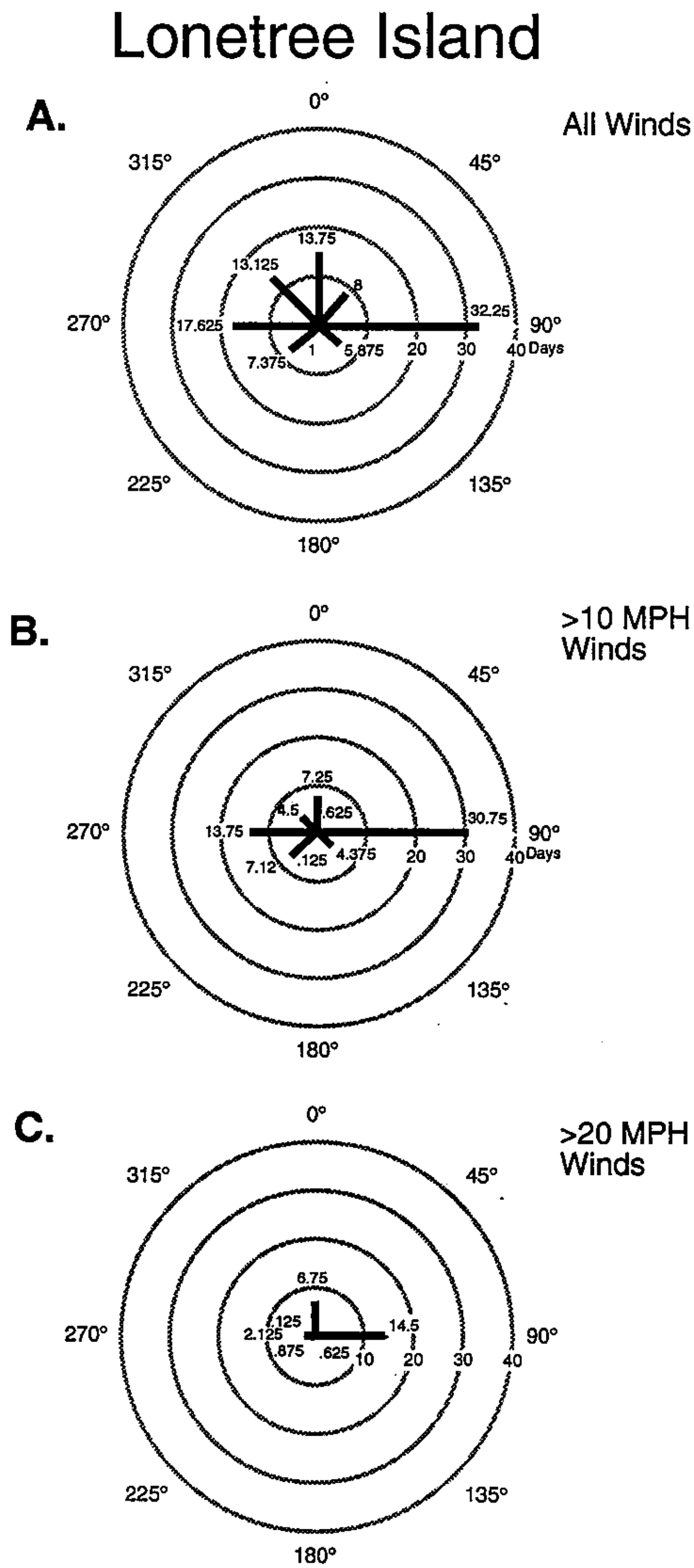
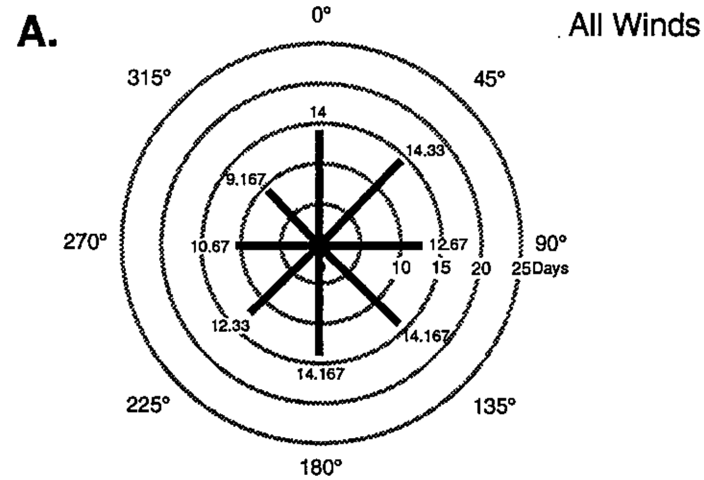
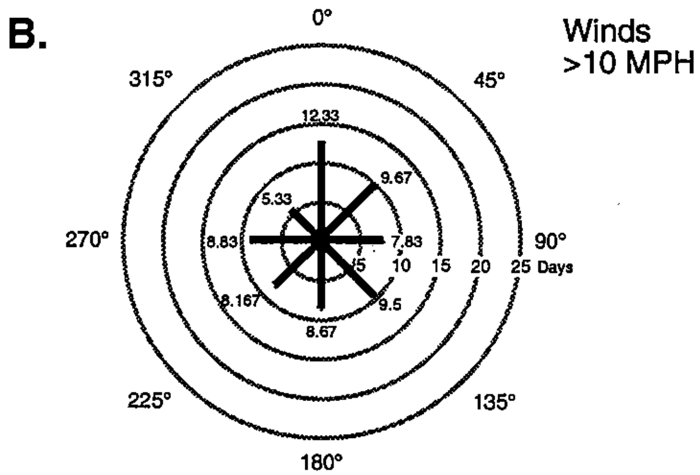


Figure 4-2. Wind data for Lonetree Island (22 November 1989 to 6 March 1990). Numbers by the bars represent number of wind days (24 hour periods) the wind blew from that direction.

Seal Island





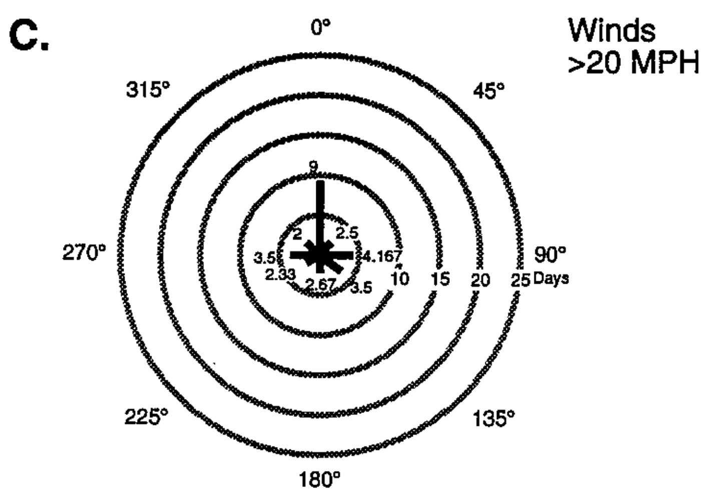


Figure 4-3. Wind data for Seal Island (22 November 1989 to 6 March 1990). Numbers by the bars represent number of wind days (24 hour periods) the wind blew from that direction.

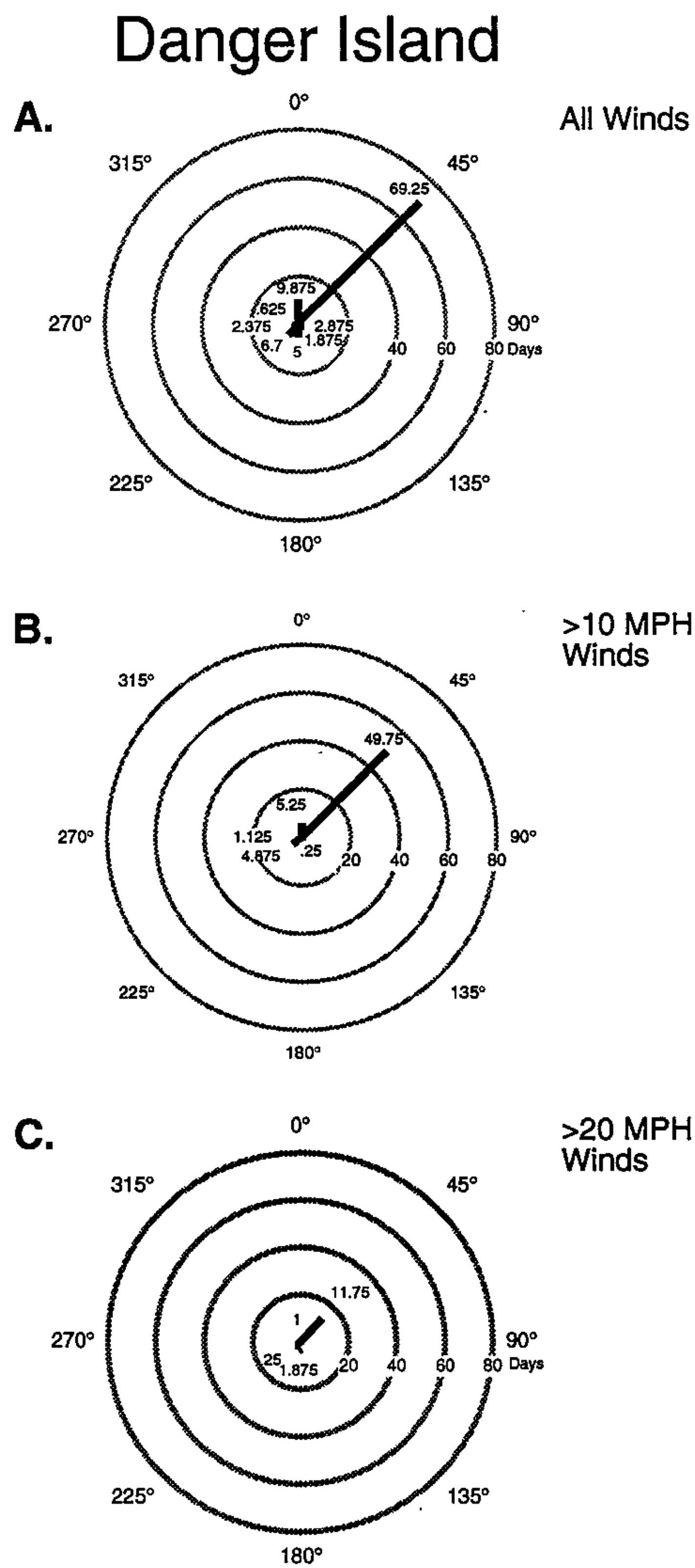


Figure 4-4. Wind data for Danger Island (22 November 1989 to 6 March 1990). Numbers by the bars represent number of wind days (24 hour periods) the wind blew from that direction.

Methods Used

The following formula was used to calculate the relative exposure of all the study sites, both geomorphological and biological, to wave action:

> **PWS Exposure Index** = [(EFP x WD 10-20 mph) + (EFP x [WD >20 mph]^2)] + [(EF 45°L x WD 10-20 mph) + (EF 45°L x [WD >20 mph]^2)] + [(EF 45°R x WD 10-20 mph) + (EF 45°R x [WD >20 mph]^2)]

EFP =	Effective fetch perpendicular to shoreline
EF 45°L =	Effective fetch 45° to the shoreline (looking left)
EF 45°R =	Effective fetch 45° to the shoreline (looking right)
WD 10-20 mph =	Number of days (24 hours) wind blew 10-20 mph (between 22 November 1989 and 6 March 1990)
WD >20 mph =	Number of days (24 hours) wind blew >20 mph (between 22 November 1989 and 6 March 1990)

The number of days with wind velocities over 20 mph are squared because wave energy flux is much greater for waves generated by the very strong winds than for the relatively mild 10-20 mph winds. This is a convention in geological studies (Price 1958). The procedure used to derive this dimensionless number involved: 1) approximating shoreline orientation to the nearest 45°; 2) measuring the effective fetch direction at the three designated angles (in nautical miles); and 3) determining the numbers of wind days for each direction from the appropriate wind record. The wind stations used for making the calculations at each site are given in Tables 4-1 and 4-2. The more remote the wind gauge, and the more topographic barriers between the wind gauge and the study site, the more inaccurate the data for the study site will be. Note the significant differences among the different recording stations (Figures 4-2, 4-3, and 4-4). The wind rose for Danger Island is highly unidirectional (from northeast), because it is influenced by a funneling effect along the east side of Latouche Island, which attains elevations of over 600 meters. Therefore, the wind data for this station were not thought to be appropriate for the stations to the north which have a more open exposure to the Sound. Data from the Danger Island station were used only for the Hogg Bay biological study site.

An example that illustrates how to calculate the Exposure Index (EI) is given in Figure 4-5. In that example, the shoreline is oriented at an angle of approximately 315°. Therefore, the effective fetch is calculated for the trend perpendicular to the shoreline

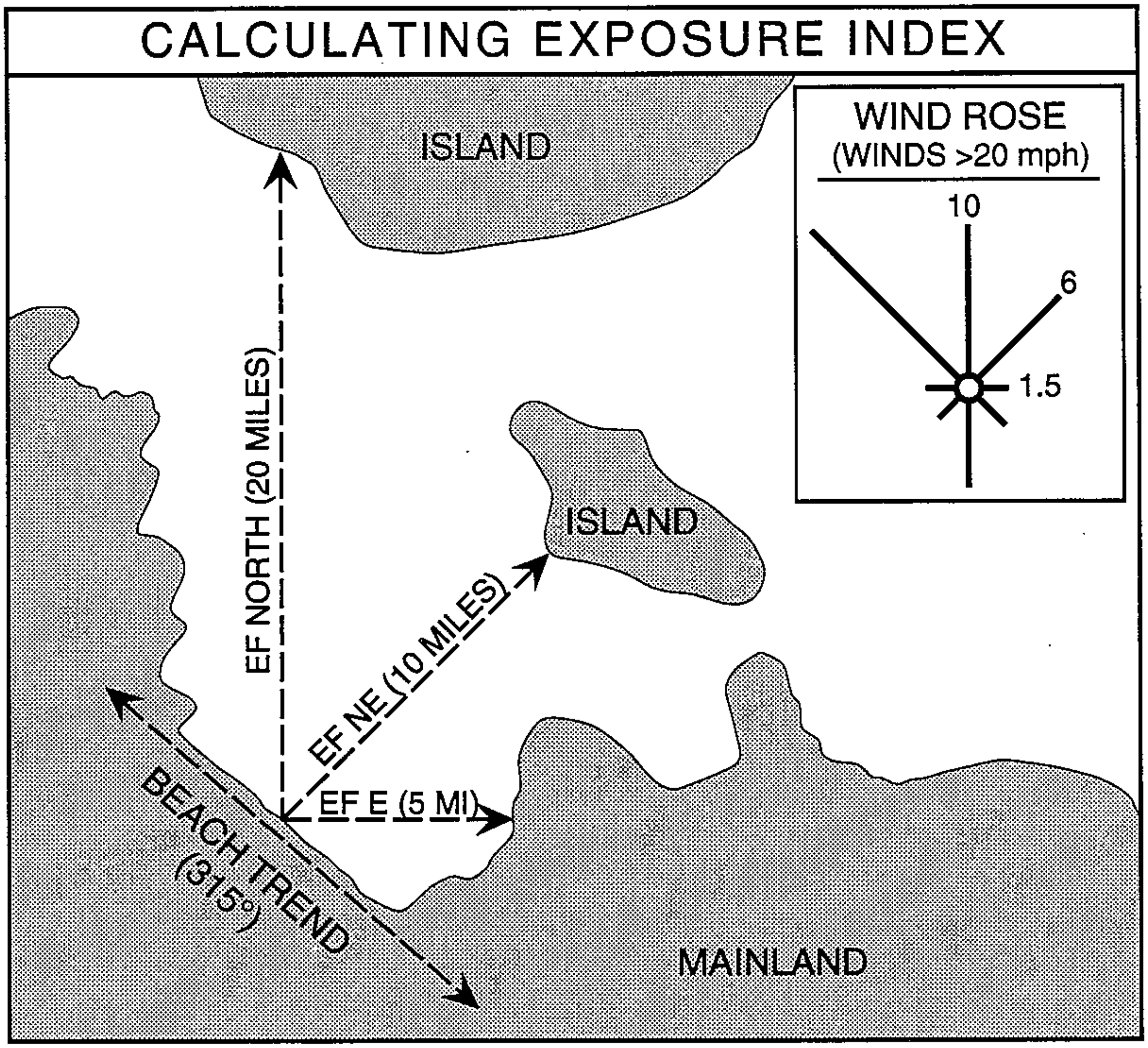


Figure 4-5. Example of how to calculate Exposure Index (EI). Wind rose gives only winds >20 mph. Winds between 10-20 mph are also used in the calculation of EI.

(northeast; 10 miles), at a 45° angle to the left (north; 20 miles), and at a 45° angle to the right (east; 5 miles). The inset wind rose in Figure 4-5 gives the wind days (WD) from the key directions (for the time interval used) when the wind blew over 20 mph: 10 WD from north, 6 WD from northeast, and 1.5 WD from the east. Assuming that the WD for velocities between 10-20 mph equal 30 (north), 20 (northeast), and 10 (east), the EI for this beach would be calculated as follows:

EI = [(EFP[10] x WD 10-20 mph [20]) + (EFP[10] x WD >20 mph[6]^2)] + [(EF 45°L[20] x WD 10-20 mph[30]) + (EF 45°L[20] x WD >20 mph[10]^2)] + [(EF 45°R[5] x WD 10-20 mph[10]) + (EF 45°R[5] x WD >20 mph[1.5]^2)] = 3,212.25

This number is dimensionless and must be compared with other sites in the same general geographic location (e.g., an oil spill site) in order for it to have meaningful application in projecting natural oil-spill cleanup rates.

Other important considerations regarding the nature of these data include:

- Swell effects are ignored. Swell is not common in Prince William Sound but it does happen.
- Decision to give the three fetch angles equal weight, because the nearshore areas are so deep significant wave refraction and energy loss would not occur offshore.
- The report by Lees et al. (1991) made the important distinction between high-tide and low-tide energy levels, which are apparent in the field. These Prince William Sound Exposure Index numbers are most representative of high-tide conditions.
- At specific study sites with complex nearshore rock outcrops and islands, energy levels vary greatly by microhabitat. These EI numbers represent the outer, more exposed components of the study sites.

The results of the calculations for all the geomorphological stations are given in Table 4-1 and Figure 4-6, and results for the biological stations are given in Table 4-2 and Figure 4-7.

Results for Geomorphological Study Sites

The EI numbers for the geomorphological sites were calculated first, in order to determine if they agreed with geomorphological and sedimentological criteria developed earlier (Michel and Hayes 1991). First, the data were plotted on a log scale, giving emphasis to the smaller numbers, and based on this plot, six classes were derived: Highly Exposed (EI > 500); Exposed (EI = 200-500); Moderately Exposed (EI = 100-200); Moderately Sheltered (EI = 50-100); Sheltered (EI = 10-50); and Highly Sheltered (EI = <10). Examination of Figure 4-6, a summary of the results for the geomorphological stations, reveals the following:

- All of the cobble/boulder platforms with berms, except station N-7 on Knight Island, were classified as Highly Exposed. Station N-7, one of the most heavily oiled of the cobble/boulder platforms as of August 1992, is classified as Exposed.
- Of the two bayhead beaches, N-18 (Sleepy Bay) was classified as barely in the Highly Exposed category and N-14 (Northwest Bay) as Moderately Sheltered.
- All of the sheltered rocky, pebble/beach tidal flat, and rubble slope stations, except station N-10 (Herring Bay), were classified as Sheltered or Highly Sheltered.

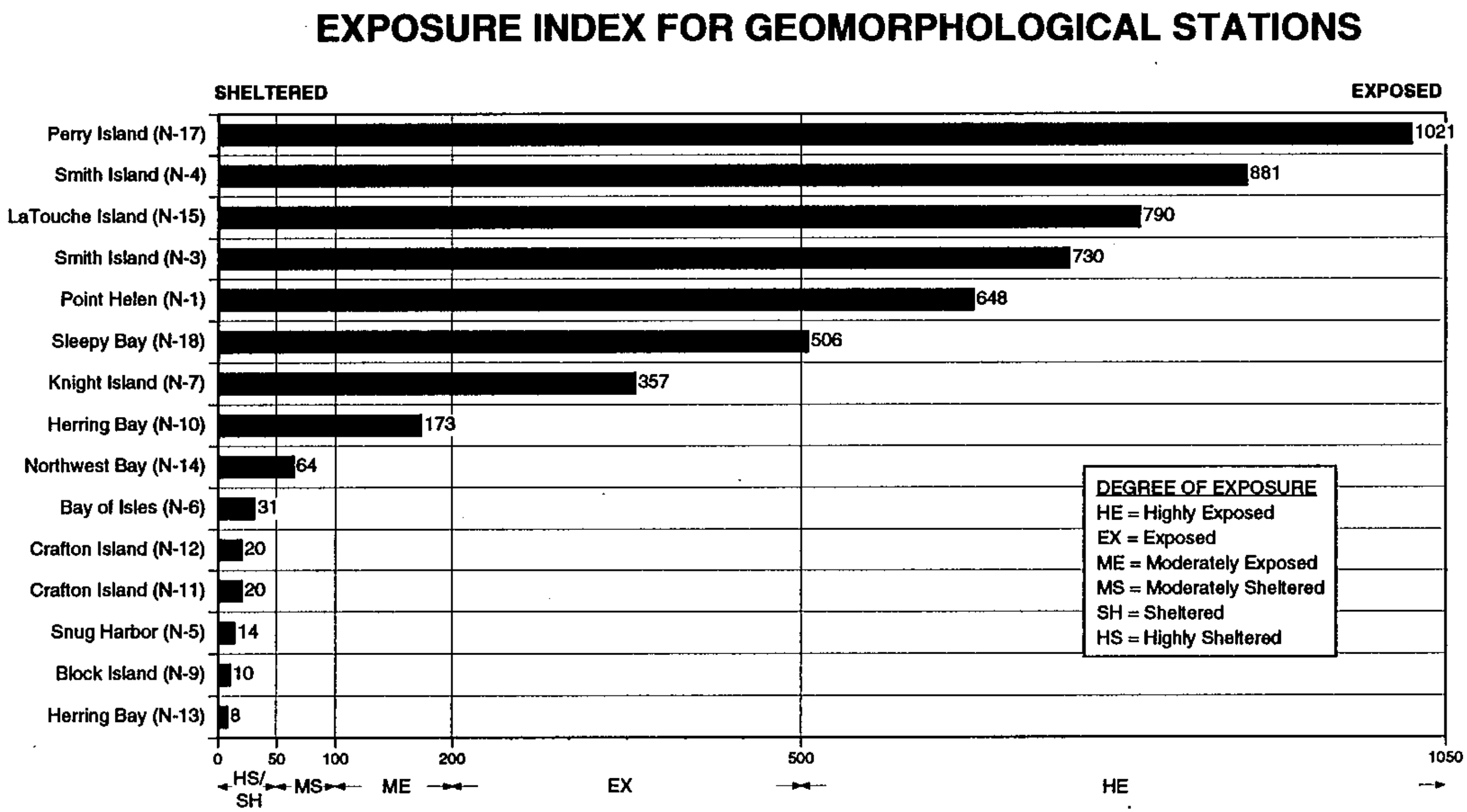


Figure 4-6. Exposure index calculations and classification–geomorphological stations.

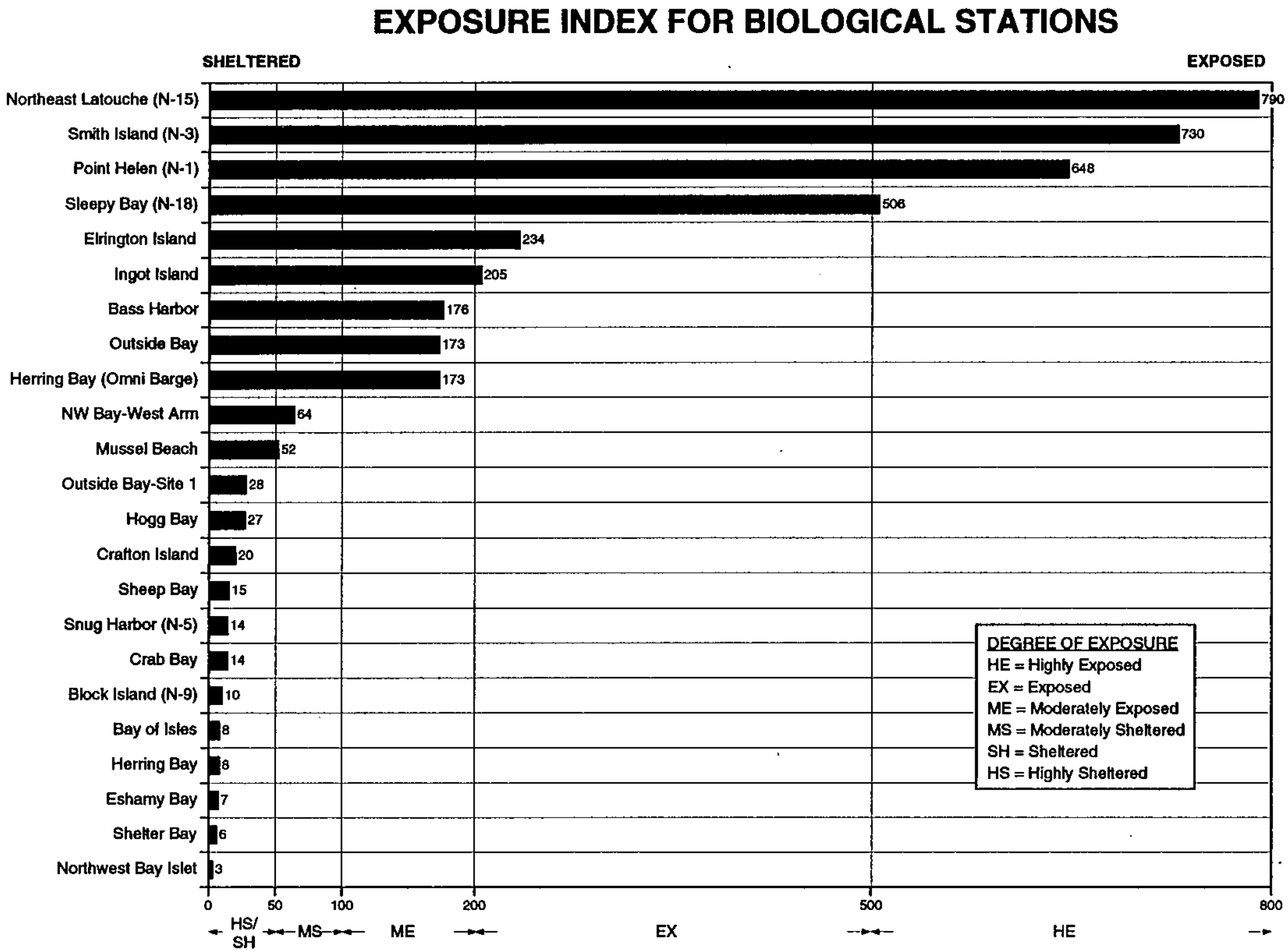


Figure 4-7. Exposure index calculations and classification–biological stations.

In short, there is an excellent correlation between the earlier concepts on sediments and geomorphology and the numbers arrived at for the Prince William Sound EI.

Another method for determining the exposure level of gravel beaches is to estimate the roundness of the individual clasts on the beach. This can be done by comparing the clasts with photographs on a chart such as the one shown in Figure 4-8, devised by Powers (1953). Folk (1974) added a logarithmic transform (ρ) scale to differentiate among the six roundness classes on a statistical basis. The photo comparison chart in Figure 4-8 was used to calculate the mean roundness of the gravel at five stations: N-1, N-5, N-7, N-13, and N-15. At each station, over 50 clasts were chosen at random along the profile line and the roundness of each clast was estimated. The correlation between exposure level and gravel roundness is illustrated in Figure 4-9, which shows a plot of gravel roundness for station N-1 at Point Helen, an exposed cobble/boulder platform with an EI of 648 (Figure 4-6), and station N-5 (Snug Harbor), a rocky rubble slope with an EI of 14. Note that all of the gravel measured at Point Helen (N-1) was round to subround, whereas all of the gravel measured at the station in Snug Harbor (N-5) was angular to subangular.

Also note the correlation between gravel roundness and exposure index shown by the plot in Figure 4-10. Clearly, in the absence of EI calculation, the roundness of the gravel on the beach is an excellent indication of its exposure, and hence the likelihood for any oil on the beach to be cleaned up by natural wave action in the Prince William Sound area.

Reference to Figure 4-10 shows that both stations N-1 and N-7 have ρ roundness values of 3.5 (subround), but considerably different EI's (N-1 = 648; N-7 = 357). As the plots in Figure 4-11 show, the values of roundness at N-7 are much more widely scattered than those for N-1. Station N-7 has a large number of clasts in the <u>angular</u> (ρ = 2-3) class, as well as a significant number in the <u>rounded</u> class (ρ = 4-5). As pointed out by Michel and Hayes (1991), this relationship is what Folk (1974) terms a <u>textural</u> <u>inversion</u>, with the more rounded clasts being inherited from a source with a different history than this particular beach. In the case of N-7, the more rounded clasts are presumably being inherited from the pre-earthquake beach, whereas the more angular particles are derived from adjacent bedrock outcrops. The more angular particles give a more accurate reading of the time it would take the surficial sediments of the beach to clean naturally. Therefore, the lower EI reading at N-7 appears to be verified by the presence of more angular sediments.

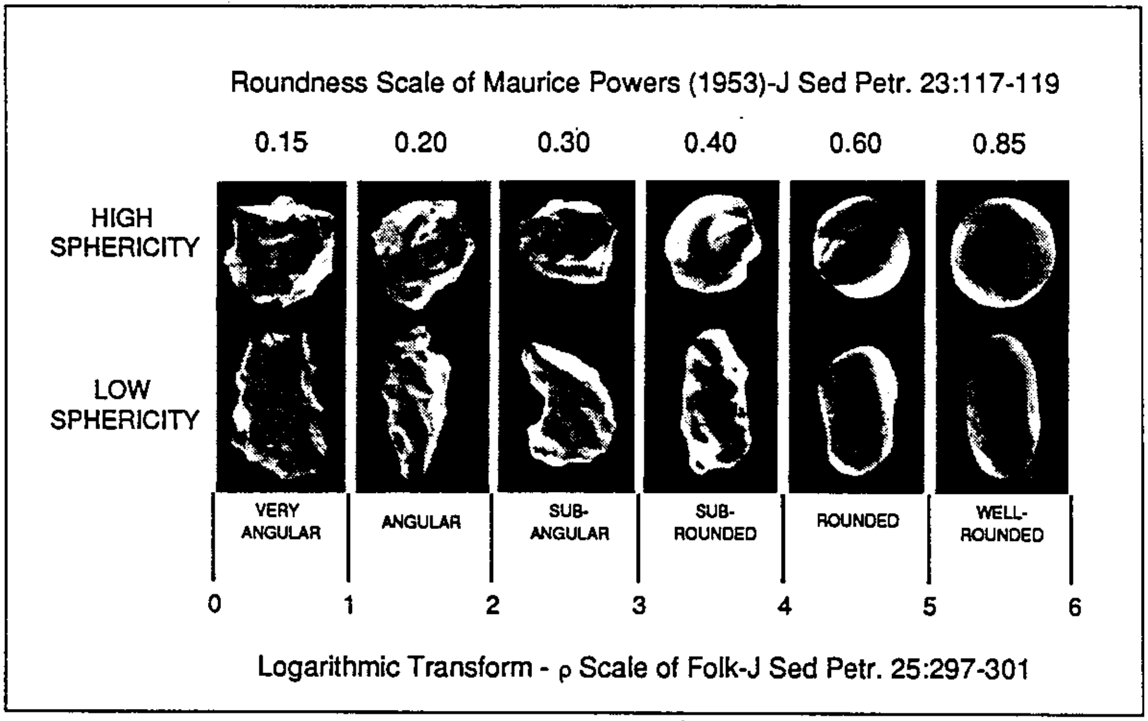


Figure 4-8. Chart used to estimate roundness of gravel clasts.

Results for Biological Study Sites

Examination of the results for the biological stations given in Table 4-2 and Figure 4-7 reveal that:

- Three of the biological stations originally classified as exposed boulder/ cobble by Lees et al. (1991), N-15, N-3, and N-1, are classified as Highly Exposed on the EI (648-790).
- Sleepy Bay, Elrington Island, and Ingot Island were classified as Exposed to just inside the Highly Exposed class (205-506).
- Bass Harbor, Outside Bay, and the Herring Bay Omni Barge site were classified as Moderately Exposed.
- Northwest Bay (West Arm) and Mussel Beach were classified as Moderately Sheltered.
- Twelve of the sites originally classified as sheltered rocky and mixed soft (Lees et al. 1991) are classified as Sheltered or Highly Sheltered on the EI (3-28).

Again, the correlation between the EI numbers and the assumptions made earlier about exposure (Lees et al. 1991) is quite strong. Only two of the sites, Sleepy Bay and Bass Harbor, give results that seem to be off intuitively, based on geomorphical and biological

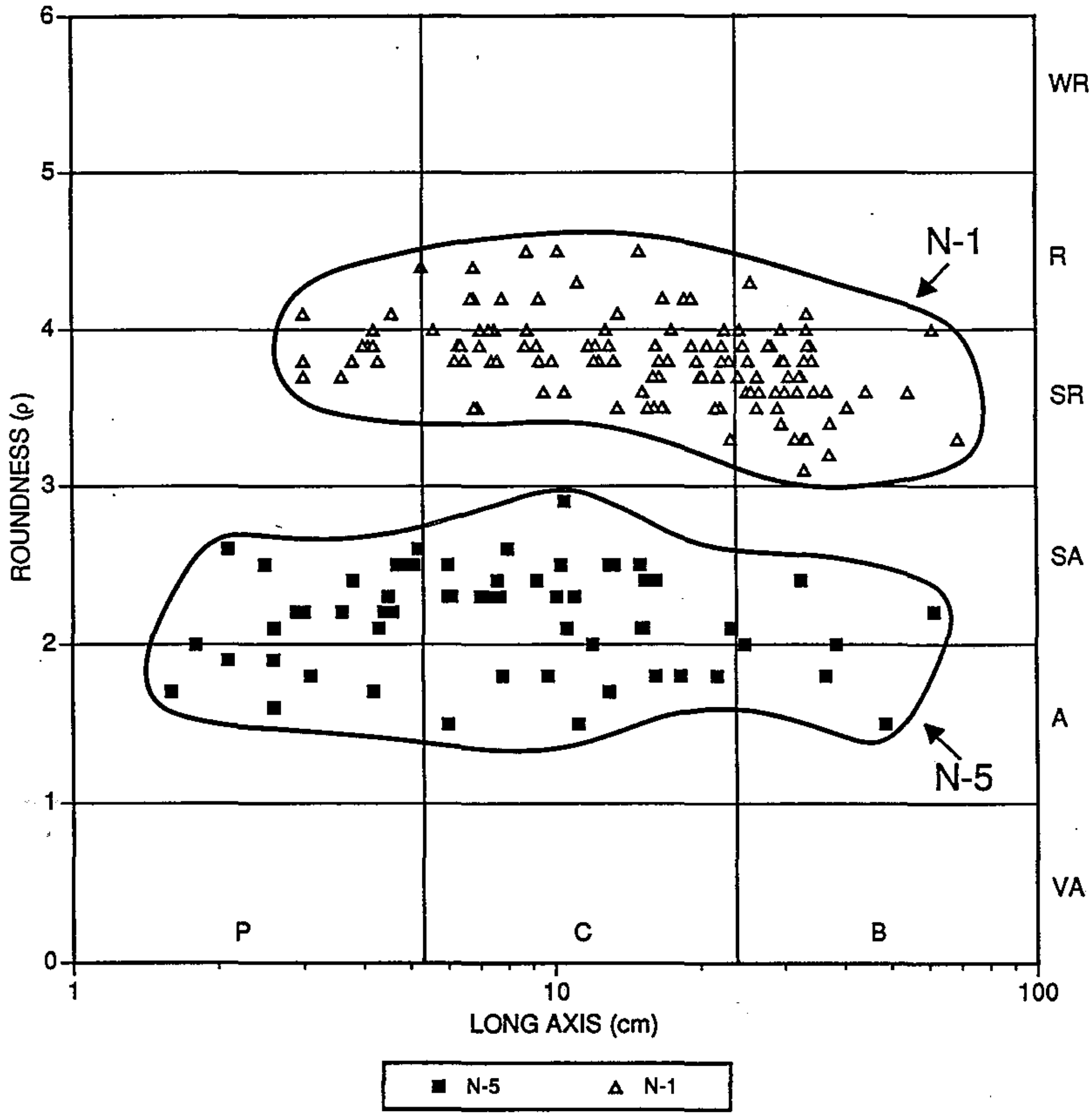


Figure 4-9. Roundness of surface clasts measured at six stations on profile N-1 and three stations on profile N-5. The gravel on the more exposed station (N-1) is much better rounded. Compare roundness values with photo comparison chart in Figure 4-8.

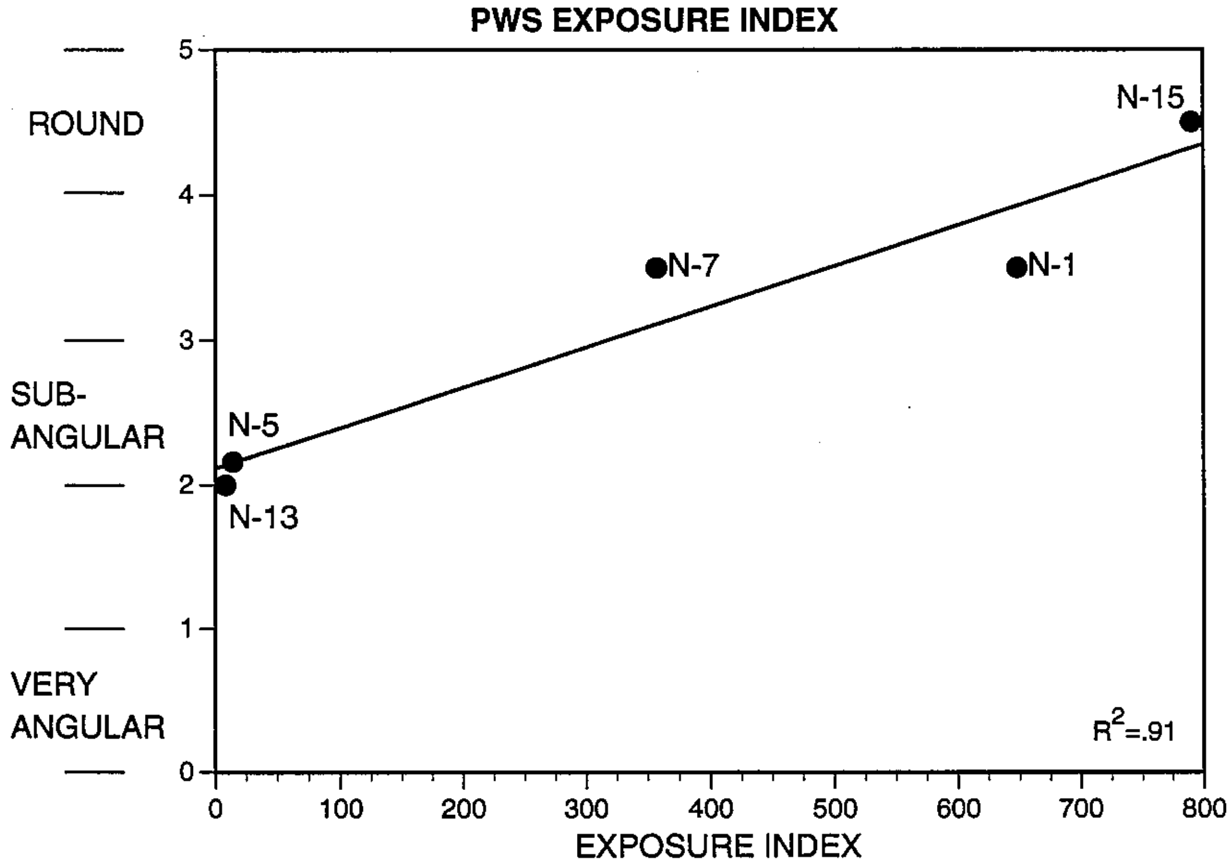


Figure 4-10. Plot of average roundness of the beach gravel versus the exposure index calculated for five of the geomorphology stations.

evidence. The reading for Sleepy Bay appears to be a bit too high and the one for Bass Harbor appears to be a bit too low. Both of these stations are located in relatively shallow embayments that open into larger water bodies. Thus, the EI for the entrance to the bay would be different than the EI for the site itself, which was calculated. It may be that swell effects, not accounted for in EI calculations, are important at the Bass Harbor site. Nonetheless, given the scarcity of wind data available and the complex morphology of the shoreline in the Sound, the correlation of EI with both geomorphological and ecological conditions at the 27 sites evaluated is remarkable.

It is important to note that many of the biological study sites are complex, and a range of energy levels may occur at the site, depending upon local sheltering by rock outcrops and differences during changing tide levels owing to complex nearshore bathymetry. The station at the north end of Elrington Island, illustrated in Figure 4-12, demonstrates

A.

B.

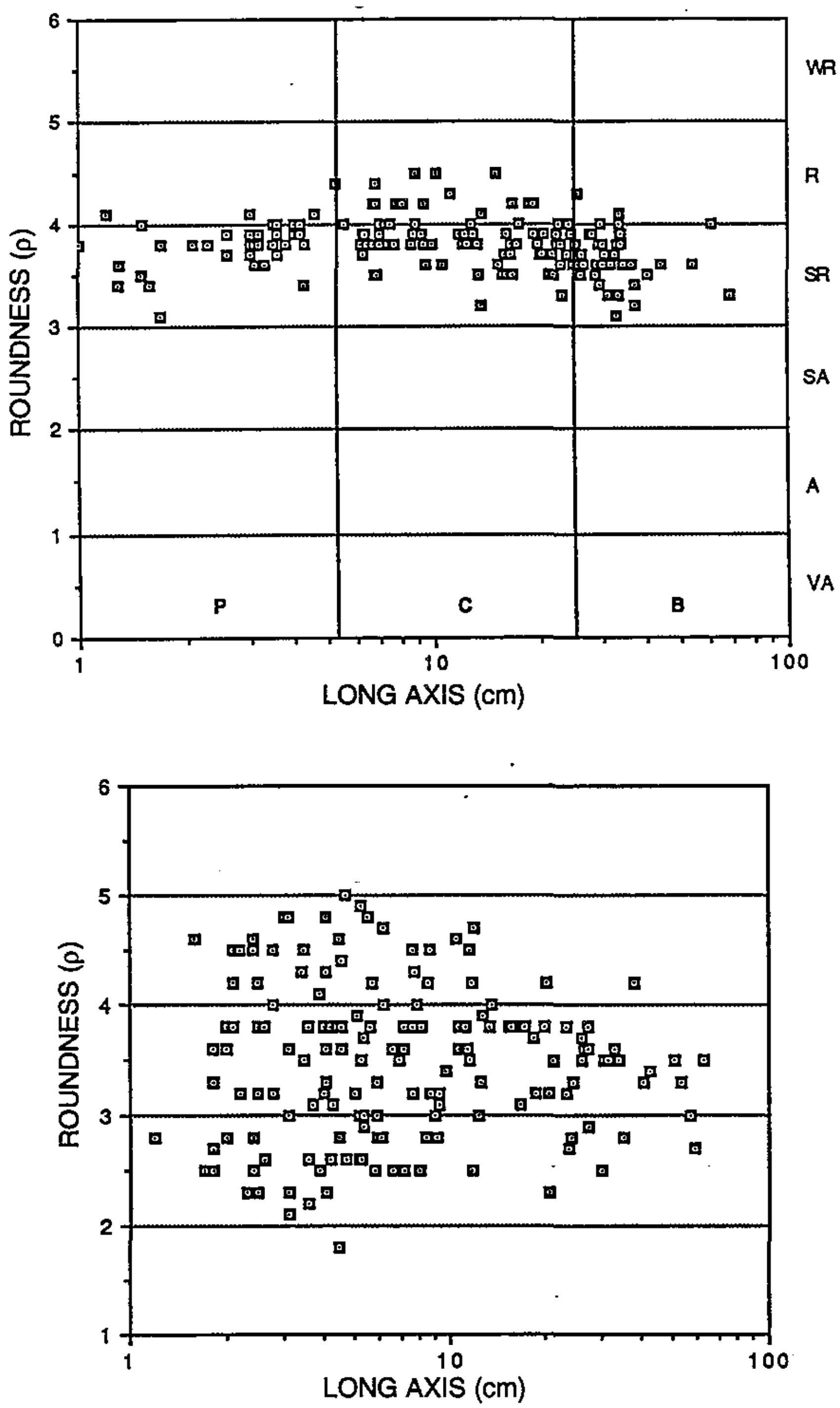


Figure 4-11. Plots of roundness versus length of long axis for all the gravel clasts measured at: (A) station N-1 (Point Helen); and (B) station N-7 (Knight Island). Note the wide scatter of readings and abundance of angular clasts at N-7.

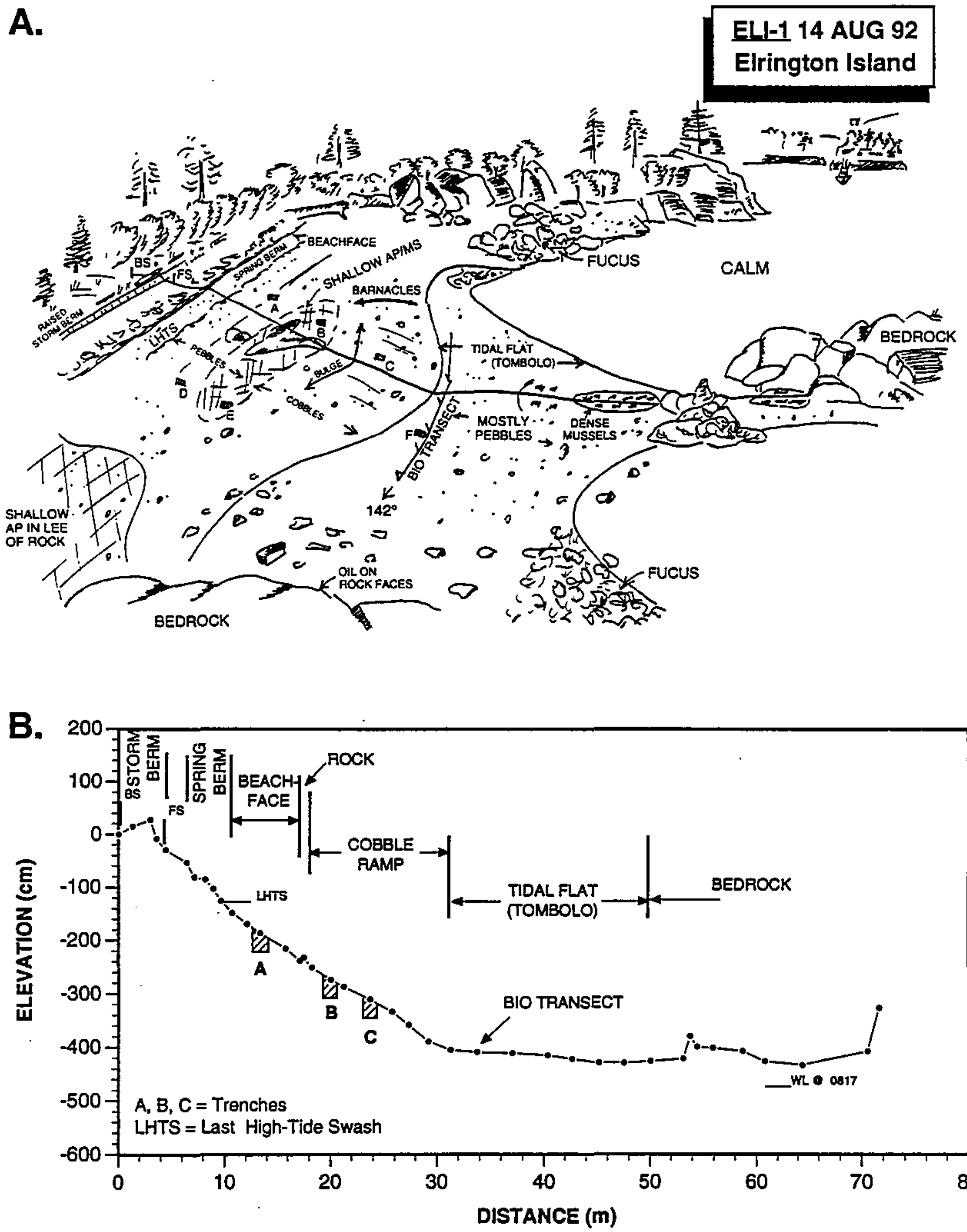


Figure 4-12. Field sketch and beach profile of Elrington Island field site on 14 August 1992.

the complexity that occurs at some of the biological sites. The mixed-soft transect at this site is on a tomboloid tidal flat in the lee of a major rock outcrop. The transect is obviously sheltered from wave attack, as were several patches of shallow subsurface asphalt pavement and mousse deposits still present in the area as of August 1992. Another bio-transect is located along the outer, exposed side of the bedrock outcrop.

A Different Wave Exposure Index

Harper et al. (1991) proposed what they called an objective Wave Exposure Index (WXI) for use during the British Columbia mapping program. These authors state that because "of the highly crenulate nature of the British Columbia shoreline," they have modified the effective fetch concept recommended by the U.S. Army Corps of Engineers (1977). The Corps recommends constructing nine radials from the point of interest at 3-degree intervals. The radials are extended until they first intersect the shoreline. Harper et al. (1991) have opted to use only the same three radials we use in our EI calculations–perpendicular to shore, 45° right and 45° left. There is no indication in their paper that they use wind data, but if "maximum fetch distances are significantly greater than their modified effective fetch... (the average length of the three radials?)..., the Wave Exposure Index is increased." This increase is made as an allowance for swell effects.

Synopsis

Working with the data at hand, which consists of somewhat limited detailed wind data, an exposure index for the Prince William Sound shoreline (PWS EI) has been derived. In general, there is an excellent correlation between geomorphic and biologic evidence for exposure and the EI, which is based on the effective fetch distance and wind duration and velocity. Twelve of the twenty-three biological stations were classified as sheltered or highly sheltered, whereas four were classified as highly exposed. Some of the biological sites are very complex, with the degree of exposure being dependent upon highly localized conditions, such as sheltering in the lee of bedrock outcrops.

This technique should also work well for other enclosed or partially enclosed coastal water bodies such as Puget Sound, the inner passage of southeast Alaska and Chesapeake Bay.

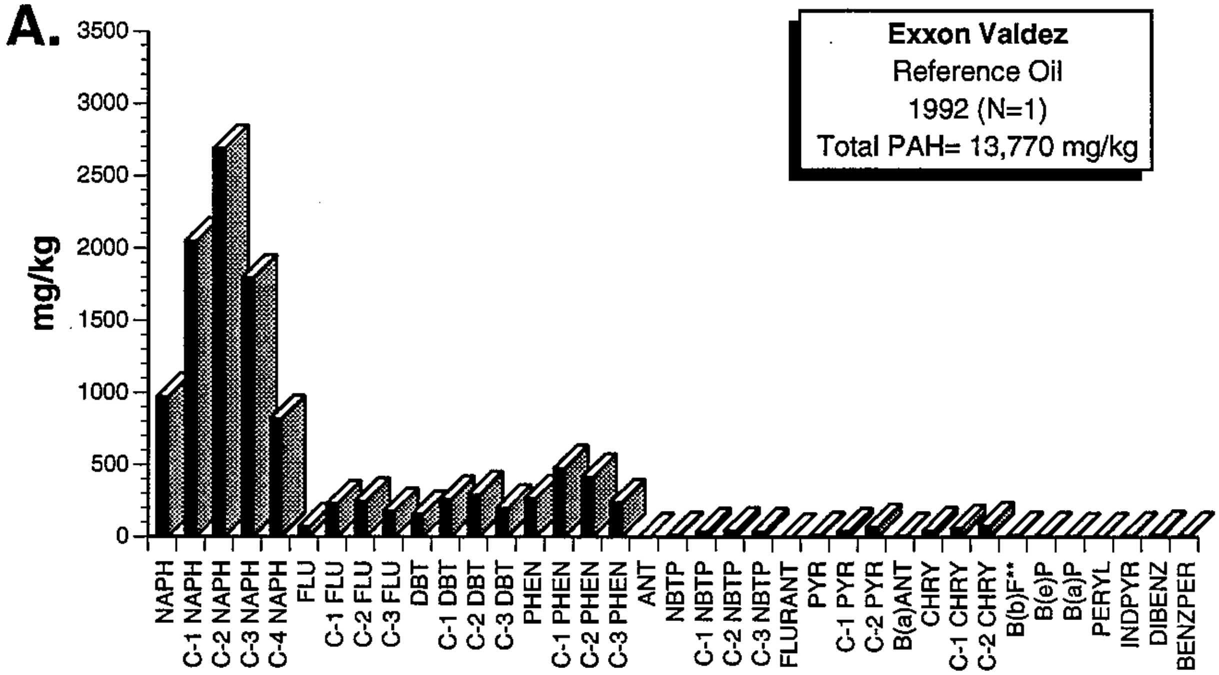
CHAPTER 5
OIL WEATHERING CHARACTERISTICS

ANALYTICAL ISSUES

Before the chemical results can be compared and temporal trends in the changes in the targeted PAHs discussed, it is important to identify analytical procedures that could affect the quantitative results. Most importantly, since the project began in 1989, two distinctive alterations in the mass spectral systems used have resulted in GC/MS data with sensitivity for the higher molecular weight compounds. In particular, the 1994 samples were run using a new mass spectral system, resulting in a systematic increase in the total targeted PAHs. Because many of the target analytes do not have authentic standards, the instrument differences can not be corrected in all cases. This effect is well demonstrated by comparing the total targeted PAHs for the *Exxon Valdez* reference oil as analyzed with the 1992 sample set and the mean of eleven analyses of the same oil with the 1994 sample set, shown in Figure 5-1. The total targeted PAHs have increased by nearly 60 percent, from 13,774 nanograms per mg (ng/mg) in 1992 to a mean of 22,000 ng/mg in 1994. Also, the relative abundance of the higher alkylated compounds in a series has changed, with the C_3 compounds as detected in the 1994 data set equal to or slightly higher than the C_2 compounds, whereas in the 1992 data set, the C_3 compounds were always lower, often by a factor of two. Therefore, it is not possible to make quantitative temporal comparisons of the PAH distributions without correcting for these systematic differences in the analytical results. However, it is possible to compare the PAH distributions among the 1994 sample set, which is the focus of this chapter.

WEATHERING PATTERNS

Although there are different methods for characterizing weathering trends of oil residues, two approaches have been used in the analysis of both the 1992 and 1994 data sets. The first approach used to analyze the PAH data is to generate <u>diagnostic</u> <u>double-ratio</u> <u>plots</u>, using the C_2- and C_3- homologues of the PAH groups of phenanthrene and dibenzothiophene. These PAH groups are both three-ringed PAHs which undergo preferential losses of the lighter homologues primarily during biodegradation but also through evaporation and dissolution. Thus, they are a valuable tool for comparing the degree of weathering among samples.



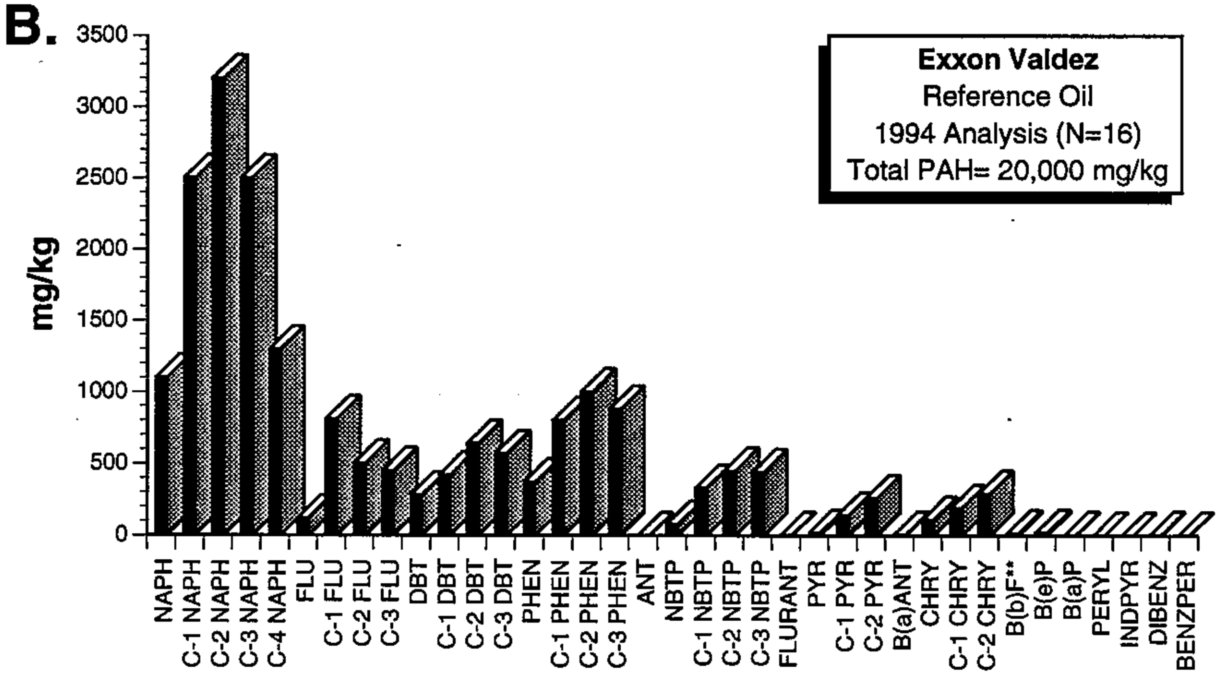


Figure 5-1. Histogram plots of the PAHs targeted for analysis in the source oil from the *Exxon Valdez*. (A) Plot for a single source oil analysis measured with the 1992 sample set. (B) Plot for an average of sixteen analyses of the same source oil measured with the 1994 sample set, using different, more sensitive instrumentation. Note that the total targeted PAHs have increased by 60 percent, and the improved sensitivity for the C_3 compounds within a group of alkylated PAHs.

The second approach is to generate histogram plots of the concentration of individual targeted PAH homologues, normalized to C_2-chrysene. This homologue of chrysene is highly resistant to biodegradation and other weathering processes. Normalizing the concentrations to this resistant PAH facilitates the comparison of weathering trends among samples with widely varying levels of residual petroleum hydrocarbons. Table 5-1 lists the abbreviations used on the PAH histogram plots. These histograms then can be interpreted to characterize the weathering stage of oil residues in each sample, relative to the original spilled oil. Comparison of the weathering stages of the 1994 samples is the primary approach for describing the temporal patterns in weathering by habitat. Four stages of PAH weathering have been defined based on a scheme proposed by Sauer et al. (1993), as follows:

Stage I (Initial Weathering) indicates oil in which evaporation has been the dominant process for the loss of PAH compounds. A small amount of loss has also occurred from dissolution. It is characterized by loss of the parent compounds of the di-aromatic hydrocarbons. Stage I oil would have been removed from natural weathering processes once it stranded onshore. No sediment samples collected in 1994 from Prince William Sound were characterized as being at Stage I.

Stage II (Moderate Weathering) indicates oil for which the C_0-, C_1-, and C_2-alkyl groups up to the three-ringed PAH compounds have been progressively reduced. Total naphthalenes have been reduced so that they are about equal to total phenanthrenes; in comparison, total naphthalenes in the original oil are about three times total phenanthrenes. These oil residues have been exposed to biodegradation and photo-oxidation over the last five years, though at reduced rates.

Stage III (Advanced Weathering) indicates oil in which the PAH pattern shows continued losses of the naphthalene, fluorene, and phenanthrene alkyl homologues. Naphthobenzothiophenes have increased in relative abundance and can even be the dominant PAH group. The characteristics C_3- and C_4-naphthalenes of the original oil are still present but they are significantly reduced.

Stage IV (Extreme Weathering) indicates oil which has undergone extensive transformation. The PAH pattern is nearly devoid of the naphthalene, fluorene, and phenanthrene alkyl homologues. Naphthobenzothiophenes are the dominant PAH group, and chrysenes have increased in relative abundance.

Table 5-1. Key for the PAH abbreviations used on Figure 5-3.

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 5-2 shows the double-ratio plot of all samples collected in 1994 except for the six samples which had PAH levels for the specific homologue below the analytical detection limits. The source oil from the *Exxon Valdez* is also shown (designated as NSC for North Slope Crude), representing the average of 11 analyses run in 1994. All samples plot along a trend toward the lower left side of the plot of increasing degree of weathering away from the source oil. Along this line, the samples fall into three distinct groupings. The four samples that plot closest to the source oil and exhibit the least amount of weathering are all from deeply penetrated oil in gravel beaches. The two samples from Pt. Helen (N-1) and one sample from Smith Island (N-3) were sediments described as HOR (heavily oiled), with TPH concentrations of 7,900-18,000 mg/kg. In contrast, the sediment sample from deep in the pebble beach at Herring Bay (N-10) was only lightly oiled, with 470 mg/kg TPH, but still characterized as least weathered.

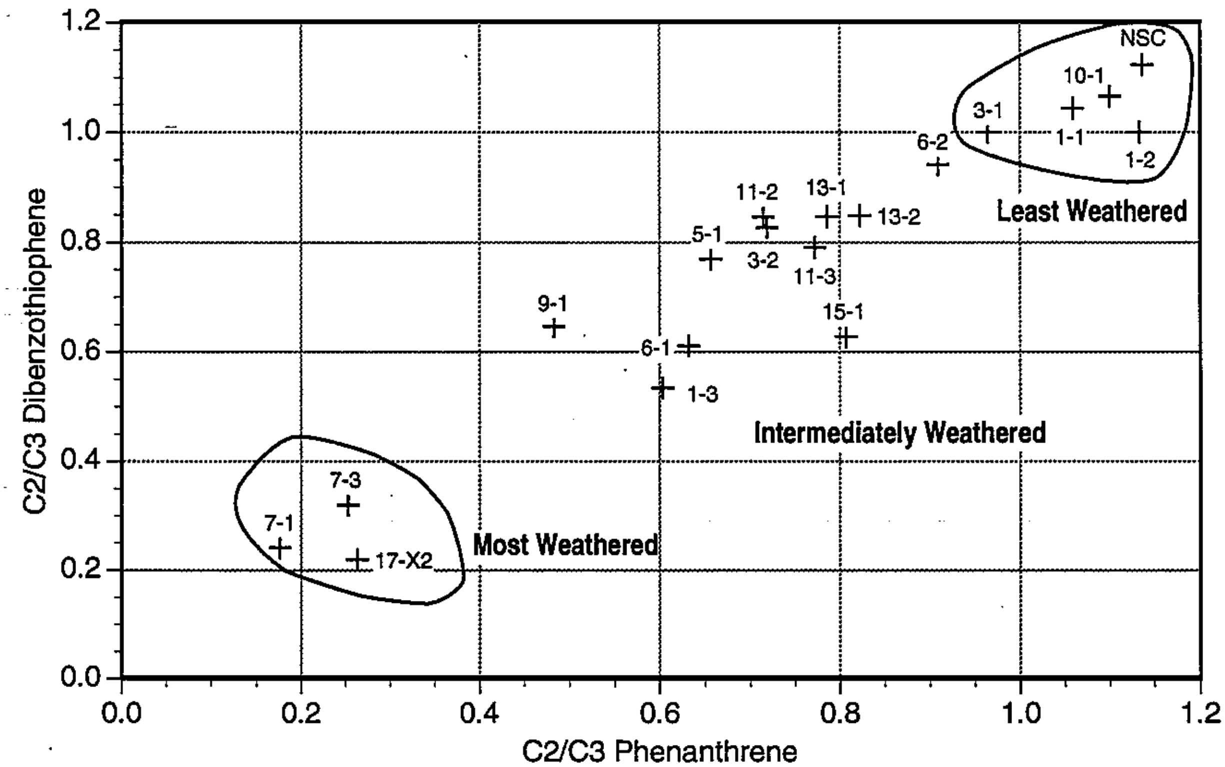


Figure 5-2. Double-ratio plot using the C_2- and C_3- homologues of phenanthrene and dibenzothiophene for all the 1994 samples which contained these compounds above the detection limits. The reference oil point (NSC) is the average of sixteen analyses conducted in 1994 for the source oil from the *Exxon Valdez*. Weathering preferentially degrades the C_2- homologues, shifting the points toward the origin. See Table 5-2 for the sample numbers.

Interestingly, the most weathered samples were also from deeply penetrated oil in the gravel beach at N-7 on Northeast Knight Island. Only two of the five samples from N-7 contained PAH levels above the detection limits for all four homologues, but these two are representative of all five. Although the oil residues in these sediments were the most weathered, they still contained significant amounts of oil, with TPH concentrations in the five samples ranging from 600-7,700 mg/kg, averaging 3,780 mg/kg. The beach at N-7 was the monitoring site where Customblen (the slow-release fertilizer) was tested for treating of subsurface oil in 1990. The NOAA profile line was used as the dividing line between the treated and control areas. At the end of the test, Inipol, the liquid oleophilic fertilizer, was applied "on an experimental basis" to the entire segment (Prince et al. 1990). Nutrient loading rates for all applications were within the normal range.

The application of fertilizers at N-7 may be responsible for the high degree of weathering of the subsurface oil. The sedimentological and geomorphological differences at N-7 (very stable profile, low slope of the platforms, well-established armor, and large amount of fine gravel in the subsurface sediments) would lead us to predict slower rather than faster weathering rates. The oil residues at N-7 in 1992 were also found to be the most weathered, even though the TPH values were much higher in 1992, ranging between 14,700 and 18,700 mg/kg.

Eleven sediments samples plotted in Figure 5-2 were classified as containing oil that is intermediately weathered. Two samples from deeply penetrated oil in gravel beaches were included in this intermediate group from: Point Helen (N-1) where sediments with an oily film overlaid a zone of heavily oiled and less weathered sediments; and Smith Island (N-3) where the more weathered sample was from a shallower depth in a different trench. Samples from 15-25 cm below the rocky rubble in two different trenches at N-13 at the Herring Bay set aside plotted in Figure 5-2 very close to each other on the upper side of the intermediate group. These samples have had very similar TPH levels and PAH distributions for several years.

Samples described as incipient asphalt pavements showed a wide range in double-ratio values. Pavement samples plotted in Figure 5-2 include the two samples from N-6 (Bay of Isles) and one each from N-5 (Snug Harbor) and N-17 (Perry Island). The pavement from Perry Island (17-X2) was collected from rock crevices along the south end of the beach. This sample plots as one of the most weathered samples. In contrast, the pavement from Bay of Isles (6-2) plots very close to the least weathered group. The other pavement samples plot in between. Pavements are difficult to characterize because they can have a highly weathered outer surface but a relatively fresh interior. It takes a very long time for thick pavements to weather to the point that they become hard. Relatively fresh oil has been found in pavements 22 years after the *Arrow* spill in Chedabucto Bay (Owens et al. 1993). The thicker oil residues in Prince William Sound are likely to form similar, persistent pavements, though they are patchy because of cleanup efforts in 1990 to remove or breakup all pavements that were found.

Another method for presenting and discussing degree of weathering for the 1994 data set is by visually comparing the distribution of PAH and the weathering stage derived from the PAH patterns. Figure 5-3 shows PAH histograms (normalized to C_2-chrysene) for the source oil and samples representative of Stages II, III, and IV weathering. Figure 5-3B shows the PAH pattern for the deep (66 cm), heavily oiled sediments at the face of the high-tide berms, at Stage II weathering. Note that the naphthalenes are still the dominant PAH, although they are greatly reduced compared to the source oil. The parent and C_1-homologue in each group have been reduced, especially for the di-aromatics (naphthalenes and fluorenes). Figure 5-3C shows the PAH pattern for the oiled sediments from 15-25 cm below the rocky rubble at N-13 in Herring Bay, at Stage III weathering. Note the continued loss of the di-aromatic PAHs, the relative increase in naphthobenzothiophenes which are now the dominant PAH group, and the relative increase in the chrysenes. Figure 5-3D shows the PAH pattern for sediments from 35-42 cm below the armor at N-7 on northeast Knight Island, at Stage IV weathering. This sample still contained 3,300 mg/kg TPH, yet the PAHs totaled only 3.8 mg/kg. All of the two- and three-ringed compounds have been lost, indicating that the aromatic hydrocarbons have undergone extensive microbial degradation. Only the most resistant naphthobenzothiophenes remain in significant amounts.

Table 5-2 lists the PAH weathering stage as determined for each 1994 sediment sample. No 1994 samples were characterized as at Stage I (initial) weathering, which reflects only evaporative losses. All of the samples at Stage II (moderate) weathering were of deeply penetrated oil in gravel beaches. Stage II+ indicates oil residues intermediate between Stages II and III, and two of the three samples at this stage were asphalt pavements. Eight samples were at Stage III and III+ (advanced) weathering, and these were mostly from the top 10 cm of sediments or incipient pavements. Examples include the moderately oiled surface sediments at N-11 on Crafton Island and at N-9 on Block Island, and the pavements at Snug Harbor and Bay of Isles. Two deep samples from the lowest trench on the gravel beach at N-7, of moderately to heavily oiled sediments, were at Stage III+ (compared to Stage IV for the upper two trenches). Seven samples were at Stage IV (extreme) weathering. These samples were mostly lightly oiled sediments (from OF to LOR) from gravel beaches at Point Helen, Perry Island, N-7, and northeast Latouche Island (N-15). The patchy pavement at Perry Island was also extremely weathered.

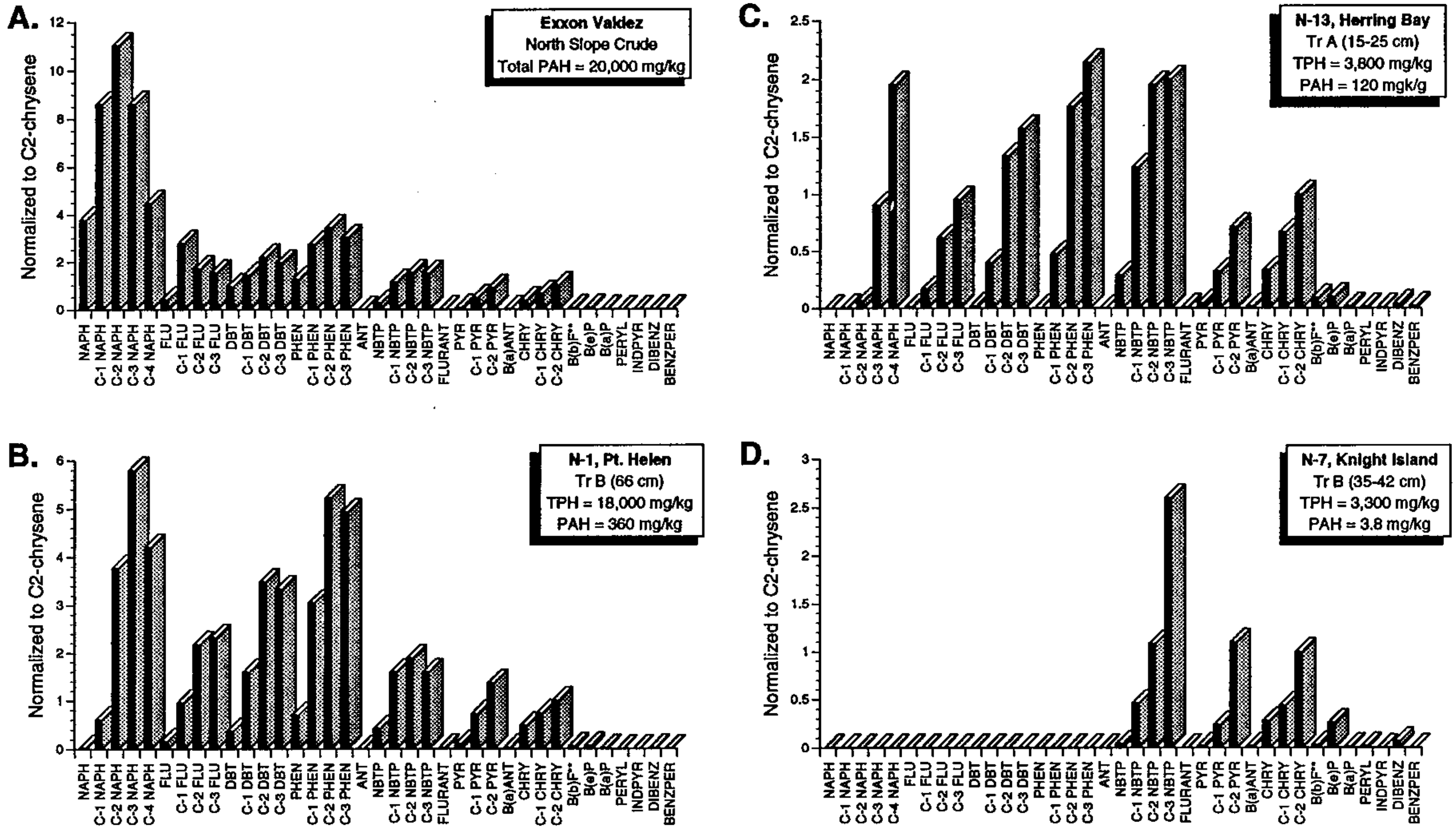


Figure 5-3. Histogram plots of targeted PAHs normalized to C_2-chrysene in: (A) the source oil; and selected 1994 samples representative of the different weathering stages from: (B) depth of 66 cm at Pt. Helen which is at Stage II (moderate) weathering; (C) 15-25 cm below the rocky rubble at N13 in Herring Bay, at Stage III (advanced) weathering; and (D) 35-42 cm below the armor at N7 on northeast Knight Island, at Stage IV (extreme) weathering.

Table 5-2. Weathering stage for the 1994 sample set.

Station No.	Zone[1]	Depth (cm)	Visual Oil[2] Description	Weathering Stage	No. on Figure 5-2
Point Helen					
N-1	Tr. B, Upper platform	30-50	OF	IV	
	Tr. B, Upper platform	66	HOR	II	1-1
	Tr. C; Lower platform	60-65	HOR	II	1-2
Smith Island					
N-3	Tr. A, Upper platform	25-35	HOR	II	3-1
	Tr. B, Upper platform	15-25	HOR	II+	3-2
Snug Harbor					
N-5	Tr. A, Raised bay bottom	0-3	AP	III	5-1
Bay of Isles					
N-6	Tr. A, Upper rocky	0-5	AP	III	6-1
	Tr. B, Upper rocky	0-5	AP	II+	6-2
NE Knight Island					
N-7	Tr. A, Upper platform	36-42	LOR	IV	
	Tr. A, Upper platform	35-45	LOR	IV	
	Tr. B; Upper platform	35-42	LOR	IV	
	Tr. C; Upper platform	35-45	MOR	III+	7-3
	Tr. C; Upper platform	55-60	HOR	III+	7-1
Block Island					
N-9	Tr. B, Tidal flat	2-10	OF	III	9-1
Herring Bay					
N-10	Low-tide zone trench	35-52	LOR	II	10-1
	High-tide trench	45-60	LOR		
	Upper rockface	0	CT		
Crafton Island					
N-11	Tr. A, Beachface	0-5	MOR	III	11-2
	Tr. A; Beachface	0-10	MOR	III	11-3
Herring Bay					
N-13	Tr. A, Upper rubble	15-25	MOR	III	13-2
	Tr. B, Upper rubble	15-25	MOR	II+	13-1
Latouche Island					
N-15	Tr. B, Upper platform	35-41	OF	IV	15-1
Perry Island					
N-17	Tr. A, Central ramp	35-45	No Oil	IV/B	
	Upper rockface	0-2	AP	IV	17-X2

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

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

There is relatively good agreement between the two approaches to characterize the degree of weathering among the 1994 sample set. All of the samples characterized as at PAH weathering Stage II plotted on Figure 5-2 in the area indicated as "least weathered". All of the samples characterized as at PAH weathering Stages II+ and III plotted on Figure 5-2 in the area indicated as "intermittently weathered". All but one sample characterized as at PAH weathering Stage III+ and IV plotted on Figure 5-2 in the "most weathered" area. The exception was sample 15-1, which contained very low PAH concentrations, totaling only 0.2 mg/kg. The double-ratio plot method starts to vary when the individual PAH volume approaches the detection level.

In summary, five years after the initial spill, oil residues ranged from moderate to extreme degrees of PAH weathering. Least weathered oil was found in heavily oiled sediments deep in gravel beaches, reflecting the very slow rates of degradation, both physical and microbial, in this habitat. The only exception was at N-7 which showed the highest degree of PAH degradation even though the TPH levels were high.

CHAPTER 6
SUMMARY

This report presents the results of NOAA's geomorphological shoreline monitoring program, during which eighteen stations have been surveyed up to thirteen times over the five-year period between September 1989 and July 1994. It has been two years since the last survey was conducted. Although each station represents a unique combination of degree of oiling, treatment history, substrate characteristics, and exposure to natural removal processes by both waves and tidal flushing, there are many lessons learned from our studies. Some of these lessons are new, and some have just been refinements or reinforcements of old lessons. These lessons are best applicable to enclosed or partially enclosed embayments, similar to Prince William Sound, that are sheltered from the large storm waves generated across open ocean fetches. Examples include Cook Inlet, the inner passage of southeast Alaska, Puget Sound, San Francisco Bay, Chesapeake Bay, and the inner coast of Maine. The major lessons are discussed below.

Lesson 1: After large-scale storm-berm relocation on coarse-grained beaches, it will take many years for the beach profile to recover completely

Large-scale berm relocation, including destruction of the high storm berm, was conducted at two of our stations, N-1 at Point Helen and N-15 on Latouche Island. Four years after the berm relocations, the storm berms at both sites had not returned to their original height, even though these sites were classified as highly exposed using the Exposure Index. On Latouche Island, the upper part of the beach profile showed a net loss of sediment. At both sites, the pile of logs and large boulders pushed back to allow excavation of the storm berm remained in disarray, aesthetically impairing the beach. With steep, rocky cliffs backing the shore, the delay in recovery of the storm berms in Prince William Sound had no serious shoreline erosion consequences. At other locations, particularly those backed by unconsolidated sediments such as glacial outwash, cliff erosion would be of greater concern.

Lesson 2: After moderate-scale berm relocation or reworking of coarse sediments on beaches, it will take several years for the sediment distribution pattern to recover

Sediment relocation and/or reworking was conducted on five of the six stations located on cobble/boulder platforms with berms. Where the sediment relocation was limited to the spring berms, such as at N-3 and N-4 on Smith Island and N-17 on Perry Island, the beach profile and sediment distribution patterns recovered completely within one storm season. In contrast, at Point Helen and Latouche Island, where the storm berm was also relocated, sediment distribution patterns took nearly four years to return to their pre-relocation condition. At Latouche Island where intensive in-place reworking of the sediment was conducted, it took four years for the very coarse armor to be restored.

Lesson 3: If very large sediments are excavated to the surface during sediment reworking, they will not be redistributed by waves

Our station at Sleepy Bay is a pebble/cobble bayhead beach that underwent extensive and multiple excavations to remove a persistent layer of heavy oil. Five years later, boulder-sized pieces of rubble remain in piles where they were originally left on the surface. The waves are not large enough to transport these boulders away from the site of the original mounds. Although the rubble piles at Sleepy Bay are not of concern since the beach grades to the east into rocky rubble which is difficult to distinguish from the man-made piles, it may be problematic at other sites. The size of sediments that will be remobilized by wave-generated currents can be estimated from the natural sediment distribution pattern on a beach.

Lesson 4: The presence of a coarse boulder armor will significantly slow natural removal of deeply penetrated subsurface oil

The importance of armoring on the persistence of subsurface oil has been one of the major lessons learned about oiled gravel beaches in Prince William Sound. The armor effectively immobilizes the subsurface sediments, except during extreme storm events, such as a ten-year storm. Heavy oil residues persist under the armor, such as at N-3 where TPH concentrations of nearly 17,000 mg/kg remain five years after the spill and extensive cleanup efforts. The oil deeply penetrated in these beaches was also the least weathered of all oil residues after five years. At N-3 on Smith Island, the subsurface oil generates chronic sheens even five years later. Where heavy oil has penetrated gravel beaches with a large, stable armor, it may be necessary to trade-off the physical disruptions to the beach profile and sediments associated with sediment reworking for more effective oil removal.

Lesson 5: Oil penetrated deeper and persisted longer where the beach sediments were thicker and the bedrock platform was flatter

Many of the gravel beaches of Prince William Sound are somewhat unique in that they were uplifted by up to 3.5 m during the 1964 earthquake. The middle and lower parts of these beaches are typically gently sloping surfaces of bedrock overlain by a mixture of sand- to-gravel-sized sediments. We found deepest penetration and longest persistence of oil where the sediment layer was thick, such as Point Helen, N-7, and N-3 on Smith Island. In contrast, on those beaches where the sediment layer was thinner and bedrock outcrops were abundant, such as Perry Island and N-4 on Smith Island, nearly all of the subsurface oil was gone after the first storm season.

Lesson 6: Where high-pressure washing of sheltered sand and gravel beaches transports the finer sediment downslope, it can take years for the sediment to return to the beachface

The best example of this problem is the beach at the head of Northwest Bay, N-14. The beach is composed mostly of granules and pebbles. Intensive high-pressure washing was conducted there, partly because heavy slicks were held by booms in Northwest Bay for a long time. Five years later, a swash bar of sediment has nearly returned to the upper beachface. Near this site, the biological survey team has also observed slowed rates of recolonization of nearshore infauna, partly because of the loss of fines and organics in the translocated sediments.

Lesson 7: Flushing of the shoreline adjacent to tidal flats increases the risk and extent of contamination of the tidal flat sediments

Western Prince William Sound has very few tidal flats, and even fewer were oiled. However, the tidal flat at Block Island was the exception in that it was heavily oiled. It is somewhat unique in that it is composed of sand to pebbles and is perched on a bedrock depression which slows the flushing rate of interstitial water. Also, the bedrock outcrops create lees which shelter the flat sediments from currents and waves. It is likely that oil originally did not adhere to or penetrate the water-saturated sediments. However, the adjacent beach of sand to pebbles was high-pressure washed. Pictures taken during flushing activities show heavy sediment plumes across the flat, and it is likely that oil and oiled sediments were washed onto the flat. Similar sites where the adjacent beach was not washed, such as at Crafton Island, show no contamination of the lower intertidal zone.

Lesson 8: Rocky rubble slopes should be of high priority for protection and cleanup because of the potential for deep penetration and slow weathering

There is a large difference in the distribution and persistence of oil on various types of sheltered rocky shores. On solid bedrock slopes with little or no surface sediment, the oil mostly remained on the surface. Heavier deposits form patches of incipient asphalt pavements. However, rocky rubble slopes have a thicker veneer of sediments that accumulate under the influence of gravity and are not sorted by waves. These sediments can be relatively permeable to oil. The set-aside in Herring Bay was the only example of this shoreline type we studied. We found oil penetration to more than 40 cm, and TPH concentrations after five years of 3,700-4,700 mg/kg.

Lesson 9: Lessons learned from case studies of oil spills should be used as guidelines, not truths, because every site is different

Spill responders rely heavily on their prior experience to make judgments about the type and degree of cleanup appropriate for a section of oiled shoreline. This approach is necessary because there is not enough knowledge or site-specific data for accurate predictions of the impacts of cleanup or how effective natural removal will be. However, it is extremely important that the unique conditions of a site be observed and understood, so that the differences among standard types of shorelines can be accounted for in the cleanup approach. The shoreline geomorphology offers many clues to those who will look carefully and see them. Understanding these clues allows the responder to optimize cleanup methods so that they are most effective and least damaging.

CHAPTER 7
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ACRONYMS

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

Appendix

Concentrations of Targeted Polynuclear Aromatic Hydrocarbons in Samples from Selected Stations July 1994

Targeted PAHs in Samples from Selected Stations - July 1994

MS FILE:	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	ED5006C
LSU ID:	N4210-88	N4210-85	N4210-63	N4210-86	N4210-89	N4210-75
SAMPLE ID:	N01-01	N01-02	N01-03	N03-01	N03-02	N05-01
LOCATION:	Pt. Helen	Pt. Helen	Pt. Helen	Smith Is.#3	Smith Is.#3	Snug Harbor
SAMPLE DATE:	7/23/94	7/23/94	7/23/94	7/24/94	7/24/94	7/22/94
TYPE:	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT
SAMPLE POP:	N=3	N=2	N=2	N=3	N=2	N=1
COMPOUNDS	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPH	0.1400	0.0330	0.0004	0.0620	0.0200	0.0180
C-1 NAPH	4.2000	1.1000	0.0011	1.8000	0.3800	0.1600
C-2 NAPH	26.0000	12.0000	0.0015	24.0000	8.2000	3.7000
C-3 NAPH	40.0000	21.0000	0.0036	34.0000	18.0000	16.0000
C-4 NAPH	29.0000	15.0000	0.0067	26.0000	19.0000	27.0000
FLU	1.1000	0.5200	0.0001	0.9600	0.3600	0.3200
C-1 FLU	6.6000	3.8000	0.0020	5.1000	3.1000	3.2000
C-2 FLU	15.0000	7.7000	0.0105	11.0000	10.0000	12.0000
C-3 FLU	16.0000	7.9000	0.0105	13.0000	16.0000	18.0000
DBT	2.5000	1.2000	0.0000	2.0000	0.6300	0.6300
C-1 DBT	11.0000	6.1000	0.0026	8.4000	5.0000	5.0000
C-2 DBT	24.0000	11.0000	0.0120	18.0000	19.0000	33.0000
C-3 DBT	23.0000	11.0000	0.0230	18.0000	23.0000	26.0000
PHEN	4.8000	2.4000	0.0012	3.5000	1.0000	1.2000
C-1 PHEN	21.0000	11.0000	0.0092	15.0000	7.9000	7.9000
C-2 PHEN	36.0000	17.0000	0.0180	27.0000	23.0000	21.0000
C-3 PHEN	34.0000	15.0000	0.0290	28.0000	32.0000	32.0000
ANT	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
NBTP	2.9000	1.4000	0.0012	2.5000	2.6000	2.6000
C-1 NBTP	11.0000	5.0000	0.0310	9.7000	10.0000	16.0000
C-2 NBTP	13.0000	5.5000	0.0530	13.0000	12.0000	26.0000
C-3 NBTP	11.0000	3.9000	0.1500	10.0000	9.0000	24.0000
FLURANT	0.1700	0.0810	0.0004	0.1000	0.1200	0.3400
PYR	0.7000	0.3900	0.0012	0.5600	0.7400	0.9300
C-1 PYR	5.0000	2.5000	0.0160	4.3000	5.0000	5.7000
C-2 PYR	9.4000	4.5000	0.0620	8.2000	9.6000	12.0000
B(a)ANT	0.1700	0.1500	0.0005	0.1200	0.1200	4.5000
CHRY	3.3000	2.2000	0.0150	2.9000	3.1000	0.0800
C-1 CHRY	5.1000	3.1000	0.0280	4.8000	4.8000	8.8000
C-2 CHRY	6.9000	3.5000	0.0540	6.6000	6.1000	14.0000
B(b)F**	0.3700	0.2500	0.0020	0.3000	0.2800	0.4100
B(e)P	0.4200	0.2300	0.0066	0.3900	0.3400	1.1000
B(a)P	0.0720	0.0077	0.0014	0.0730	0.0300	1.6000
PERYL	0.0000	0.0000	0.0008	0.0000	0.0000	0.0370
INDPYR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DIBENZ	0.1100	0.0630	0.0062	0.1200	0.0720	0.2500
BENZPER	0.0390	0.0050	0.0013	0.0470	0.0180	0.1000
Total Target AH:	360.0000	180.0000	0.5600	300.0000	250.0000	330.0000
TPH (g/kg)	17.9000	7.8700	1.0200	15.9000	16.8000	32.5000
TTAH/TPH	20.1117	22.8717	0.5490	18.8679	14.8810	10.1538

Targeted PAHs in Samples from Selected Stations - July 1994

MS FILE:	AVERAGE	ED5006D	ED4305G	ED4305E	ED4305F	ED4305D
LSU ID:	N4210-81	N4210-69	N4210-95	N4210-91	N4210-92	N4210-87
SAMPLE ID:	N06-01	N06-02	N07-01	N07-02	N07-03	N07-04
LOCATION:	Bay of Isles	Bay of Isles	Knight Island	Knight Island	Knight Island	Knight Island
SAMPLE DATE:	7/23/94	7/23/94	7/25/94	7/25/94	7/25/94	7/25/94
TYPE:	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT
SAMPLE POP:	N=3	N=1	N=1	N=1	N=1	N=1
COMPOUNDS	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPH	0.0026	0.1900	0.0020	0.0000	0.0016	0.0000
C-1 NAPH	0.0280	0.0850	0.0056	0.0000	0.0030	0.0000
C-2 NAPH	0.7500	4.8000	0.0100	0.0000	0.0087	0.0000
C-3 NAPH	4.8000	17.0000	0.0280	0.0000	0.0630	0.0000
C-4 NAPH	9.3000	19.0000	0.3400	0.0000	0.4200	0.0000
FLU	0.0680	0.2200	0.0000	0.0000	0.0000	0.0000
C-1 FLU	1.2000	3.3000	0.0000	0.0000	0.0000	0.0000
C-2 FLU	5.7000	9.5000	0.1500	0.0000	0.2100	0.0000
C-3 FLU	11.0000	12.0000	1.0000	0.0000	0.8700	0.0000
DBT	0.2200	0.5100	0.0000	0.0000	0.0000	0.0000
C-1 DBT	2.3000	6.0000	0.0000	0.0000	0.0280	0.0000
C-2 DBT	11.0000	16.0000	0.5800	0.0000	0.6400	0.0000
C-3 DBT	18.0000	17.0000	2.4000	0.0000	2.0000	0.0000
PHEN	0.2600	1.2000	0.0000	0.0000	0.0073	0.0000
C-1 PHEN	3.0000	9.6000	0.0680	0.0000	0.0100	0.0000
C-2 PHEN	12.0000	20.0000	0.3700	0.0000	0.4800	0.0000
C-3 PHEN	19.0000	22.0000	2.1000	0.0000	1.9000	0.0000
ANT	0.0110	0.0000	0.0000	0.0000	0.0000	0.0000
NBTP	1.0000	1.9000	0.0340	0.0190	0.0380	0.0000
C-1 NBTP	5.9000	9.2000	1.3000	0.2300	1.2000	0.0000
C-2 NBTP	8.9000	14.0000	2.1000	0.5400	1.9000	0.2000
C-3 NBTP	9.2000	18.0000	1.8000	1.3000	1.7000	0.9500
FLURANT	0.0430	0.1000	0.0032	0.0000	0.0000	0.0000
PYR	0.7500	0.5300	0.1500	0.0086	0.0970	0.0000
C-1 PYR	4.0000	3.5000	0.7500	0.1200	0.5500	0.0600
C-2 PYR	7.3000	6.3000	1.6000	0.5500	1.3000	0.3200
B(a)ANT	0.0990	0.1100	0.0067	0.0092	0.0062	0.0086
CHRY	3.0000	2.8000	0.5700	0.1400	0.4400	0.0690
C-1 CHRY	4.0000	4.9000	0.6800	0.2200	0.6200	0.1100
C-2 CHRY	5.5000	7.8000	0.9700	0.5000	0.9700	0.3000
B(b)F**	3.4000	0.2600	0.0560	0.0150	0.0500	0.0100
B(e)P	0.4700	0.0620	0.0120	0.1300	0.0920	0.0990
B(a)P	0.1500	0.0000	0.1200	0.0049	0.0200	0.0150
PERYL	0.0310	0.0000	0.0067	0.0091	0.0097	0.0070
INDPYR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DIBENZ	0.1200	0.1100	0.0260	0.0340	0.0260	0.0280
BENZPER	0.0360	0.0450	0.0079	0.0000	0.0083	0.0096
Total Target AH:	150.0000	230.0000	17.0000	3.8000	16.0000	2.2000
TPH (g/kg)	27.3000	35.7000	7.7200	3.3300	4.4600	2.8500
TTAH/TPH	5.4945	6.4426	2.2021	1.1411	3.5874	0.7719

Targeted PAHs in Samples from Selected Stations - July 1994

MS FILE:	AVERAGE	ED4296E	AVERAGE	ED4304H	ED4296F	ED5006E
LSU ID:	N4210-65	N4210-64	N4210-94	N4210-80	N4210-78	N4210-77
SAMPLE ID:	N07-05	N09-01	N10-01	N11-02	N11-03	N13-01
LOCATION:	Knight Island	Block Island	Herring Bay	Crafton Island	Crafton Island	Herring Bay
SAMPLE DATE:	7/25/94	7/21/94	7/25/94	7/20/94	7/20/94	7/21/94
TYPE:	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT
SAMPLE POP:	N=2	N=1	N=2	N=1	N=1	N=1
COMPOUNDS	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPH	0.0000	0.0002	0.0018	0.0000	0.0000	0.0000
C-1 NAPH	0.0000	0.0002	0.0600	0.0000	0.0017	0.0900
C-2 NAPH	0.0000	0.0019	1.1000	0.4000	0.0770	2.7000
C-3 NAPH	0.0000	0.0050	1.6000	2.2000	0.3300	8.5000
C-4 NAPH	0.0000	0.0082	1.1000	2.7000	0.3500	11.0000
FLU	0.0000	0.0000	0.0550	0.0220	0.0042	0.1300
C-1 FLU	0.0000	0.0013	0.2600	0.4000	0.0610	1.5000
C-2 FLU	0.0000	0.0053	0.5000	1.3000	0.1800	4.6000
C-3 FLU	0.0000	0.0083	0.5200	1.7000	0.2700	6.9000
DBT	0.0000	0.0002	0.1100	0.0610	0.0110	0.3300
C-1 DBT	0.0000	0.0021	0.4300	0.6700	0.1100	2.7000
C-2 DBT	0.0000	0.0084	0.8000	2.2000	0.3400	8.3000
C-3 DBT	0.0160	0.0130	0.7400	2.6000	0.4300	9.8000
PHEN	0.0000	0.0009	0.2100	0.0620	0.0150	0.4200
C-1 PHEN	0.0000	0.0018	0.8200	0.9000	0.1700	4.2000
C-2 PHEN	0.0000	0.0082	1.2000	2.5000	0.4400	11.0000
C-3 PHEN	- 0.0000	0.0170	1.0000	3.5000	0.5700	14.0000
ANT	0.0000	0.0003	0.0000	0.0081	0.0000	0.0000
NBTP	0.0019	0.0022	0.0990	0.3400	0.0660	1.2000
C-1 NBTP	0.0490	0.0120	0.3400	1.3000	0.3000	5.7000
C-2 NBTP	0.2200	0.0250	0.4100	2.2000	0.5300	7.8000
C-3 NBTP	0.4400	0.0380	0.3200	2.2000	0.5600	7.5000
FLURANT	0.0000	0.0023	0.0053	0.0240	0.0027	0.0570
PYR	0.0028	0.0019	0.0240	0.1000	0.0140	0.3200
C-1 PYR	0.0360	0.0041	0.1600	0.5700	0.0980	2.1000
C-2 PYR	0.1700	0.0099	0.2900	1.2000	0.2300	4.3000
B(a)ANT	0.0014	0.0008	0.0076	0.4700	0.0043	0.0800
CHRY	0.2100	0.0055	0.1100	0.4700	0.0960	1.6000
C-1 CHRY	0.1300	0.0085	0.1800	0.7900	0.1800	3.1000
C-2 CHRY	0.2700	0.0160	0.2100	1.2000	0.2800	4.5000
B(b)F**	0.0110	0.0036	0.0140	0.0880	0.0210	0.1200
B(e)P	0.0290	0.0031	0.0140	0.1200	0.0310	0.2900
B(a)P	0.0057	0.0013	0.0046	0.0180	0.0075	0.0380
PERYL	0.0017	0.0018	0.0000	0.0140	0.0083	0.0000
INDPYR	0.0000	0.0011	0.0000	0.0000	0.0000	0.0000
DIBENZ	0.0085	0.0026	0.0037	0.0350	0.0150	0.0510
BENZPER	0.0014	0.0006	0.0012	0.0130	0.0050	0.0170
Total Target AH:	1.6000	0.2200	13.0000	32.0000	5.8000	120.0000
TPH (g/kg)	0.6000	0.0800	0.4700	2.0900	0.7900	4.7400
TTAH/TPH	2.6667	2.7500	27.6596	15.3110	7.3418	25.3165

Targeted PAHs in Samples from Selected Stations - July 1994

MS FILE:	ED4302C	AVERAGE	ED4296D	ED4301C	NSC AVG
LSU ID:	N4210-82	N4210-62	N4210-93	N4210-66	NSC REF
SAMPLE ID:	N13-02	N15-01	N17-01	N17-X02	
LOCATION:	Herring Bay	NE LaTouche	Perry Island	Perry Island	
SAMPLE DATE:	7/21/94	7/23/94	7/26/94	7/26/94	
TYPE:	SEDIMENT	SEDIMENT	SEDIMENT	SEDIMENT	
SAMPLE POP:	N=1	N=6	N=1	N=1	N=16
COMPOUNDS	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)	ng/mg (wet)
NAPH	0.0000	0.0002	0.0000	0.0000	1100.0000
C-1 NAPH	0.0120	0.0003	0.0000	0.0000	2500.0000
C-2 NAPH	0.1400	0.0007	0.0000	0.0000	3200.0000
C-3 NAPH	1.9000	0.0014	0.0000	0.0000	2500.0000
C-4 NAPH	4.1000	0.0021	0.0000	0.0210	1300.0000
FLU	0.0280	0.0001	0.0000	0.0000	120.0000
C-1 FLU	0.3500	0.0012	0.0000	0.0000	810.0000
C-2 FLU	1.3000	0.0027	0.0000	0.0840	500.0000
C-3 FLU	2.0000	0.0041	0.0000	0.1800	450.0000
DBT	0.0400	0.0002	0.0000	0.0000	280.0000
C-1 DBT	0.8400	0.0007	0.0000	0.0000	420.0000
C-2 DBT	2.8000	0.0040	0.0000	0.0770	640.0000
C-3 DBT	3.3000	0.0064	0.0000	0.3500	570.0000
PHEN	0.0110	0.0011	0.0019	0.0075	370.0000
C-1 PHEN	1.0000	0.0047	0.0018	0.0470	800.0000
C-2 PHEN	3.7000	0.0090	0.0020	0.1000	1000.0000
C-3 PHEN	4.5000	0.0112	0.0052	0.3800	880.0000
ANT	0.0000	0.0009	0.0005	0.0000	0.0000
NBTP	0.6100	0.0005	0.0020	0.0190	79.0000
C-1 NBTP	2.6000	0.0061	0.0100	0.3600	330.0000
C-2 NBTP	4.1000	0.0151	0.0330	1.1000	450.0000
C-3 NBTP	4.2000	0.0637	0.0600	2.6000	440.0000
FLURANT	0.0180	0.0007	0.0091	0.0093	3.3000
PYR	0.0960	0.0013	0.0082	0.0650	19.0000
C-1 PYR	0.6800	0.0050	0.0055	0.3600	140.0000
C-2 PYR	1.5000	0.0150	0.0096	1.0000	260.0000
B(a)ANT	0.0370	0.0019	0.0067	0.0100	6.2000
CHRY	0.7100	0.0047	0.0091	0.5100	110.0000
C-1 CHRY	1.4000	0.0090	0.0110	0.6900	190.0000
C-2 CHRY	2.1000	0.0285	0.0220	1.0000	290.0000
B(b)F**	0.1900	0.0035	0.0099	0.0620	16.0000
B(e)P	0.2100	0.0037	0.0057	0.2300	19.0000
B(a)P	0.0380	0.0019	0.0051	0.0210	3.7000
PERYL	0.0220	0.0017	0.0014	0.0200	1.1000
INDPYR	0.0190	0.0002	0.0023	0.0160	0.1000
DIBENZ	0.0850	0.0059	0.0039	0.0940	6.0000
BENZPER	0.0440	0.0004	0.0015	0.0420	2.6000
Total Target AH:	45.0000	0.2200	0.2300	9.5000	20000.0000
TPH (g/kg)	3.7500	0.7600	0.0500	7.3300	1000.0000
TTAH/TPH	12.0000	0.2895	4.6000	1.2960	20.0000