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

Volume I 1991 Geomorphological Shoreline Monitoring Survey

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NOTICE

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INTRODUCTION

Since September 1989, the Hazardous Materials Response and Assessment Division of the National Oceanic and Atmospheric Administration (NOAA) has conducted surveys of the geomorphological changes and oil distribution at selected shoreline stations throughout Prince William Sound (PWS), Alaska. This work was designed to provide the scientific basis for decision making by the Federal On-Scene Coordinator of the *Exxon Valdez* oil spill, on shoreline treatment in 1990 and 1991. Among the 18 original stations, sites were set aside (not treated) for research. The environmental effects and oil persistence on untreated shorelines were compared with those that had undergone different types of physical and biological treatment. The study results for the period September 1989 to January 1991 have been reported in Michel and Hayes (1991).

After the January 1991 survey, NOAA decided to continue monitoring the shoreline stations as part of a long-term program to monitor the fate of the stranded oil on various shoreline types and physical settings, the effectiveness of various treatment methodologies, and the weathering patterns of the residual oil. The focus of this program is to better understand the tradeoffs between different types and degrees of shoreline treatment techniques and natural recovery. As the Scientific Support Coordinator to the U. S. Coast Guard, NOAA must frequently make recommendations on appropriate shoreline cleanup methods during oil spills. The shoreline contaminated during the *Exxon Valdez* oil spill included many different geomorphological types and degrees of exposure to wave action, which were aggressively treated with a wide range of methods.

NOAA's long-term monitoring program is particularly important because:

1) It is the only program that has been completely free of legal restrictions throughout its duration, and it will continue to be so.

2) The results have been published in their entirety, so they are available to the spill-response community.

3) Other shoreline monitoring programs that conducted as part of the spill-response support effort (Exxon and State of Alaska) have been terminated or have an uncertain future.

4) The NOAA program includes a large database of detailed chemical compositional information, starting with samples collected within the first few days of the spill. Throughout the surveys, samples of surface and subsurface oil have been collected for chemical characterization by gas chromatography/mass spectrometry (GC/MS). This database provides a valuable record for comparison of the weathering trends and rates for the different shoreline treatments and the set-aside stations.

This report summarizes the results of the August 1991 survey change. It will also include a detailed discussion of the chemical weathering rates and comparisons, once the chemical analyses have been completed by Louisiana State University (LSU). Thus, this draft report includes primarily the geomorphological results, a brief discussion of the gross changes in oil concentration at each station, and a draft summary of the effectiveness of berm relocation as applied in PWS.

ACKNOWLEDGMENTS

This report on the August 1991 geomorphological field survey of the *Exxon Valdez* spill site in PWS, Alaska, is a part of the continuing monitoring survey sponsored by the Hazardous Materials Response and Assessment Division of NOAA, David Kennedy, Division Chief and Robert Pavia, Project Technical Representative. Field logistical support was provided by the charter vessel *Renown*. Captain Randy Becker and First Mate Ray Mathis were extremely cooperative and assisted in some phases of the field work. Debra Scholz of Research Planning, Inc. (RPI) assisted the authors with the field survey. Graphics and other technical support were provided by Jeff Dahlin, Joe Holmes, Becky Cook, and Tom Simpson of the RPI staff.

Chapter 1

STUDY METHODS AND DATA COLLECTED

During this survey, 13 of the original 18 survey sites were revisited. Three profiles were surveyed at station N-15. Also, the berm relocation site KN-405A, near the south end of Knight Island, was visited by Hayes on June 4, 1991, as part of a special site review requested by the 1991 shoreline cleanup Technical Assistance Group (TAG). The stations omitted were sites deemed to be clean or of little scientific merit, or where the survey markers had been removed by cleanup crews.

The following data were collected at each station:

1) A topographic profile was run perpendicular to the beach, along which details of the morphology and oil distribution patterns were noted.

2) The station was sketched in detail, highlighting the distribution of oil, if present, and the effects of cleanup activities, such as berm relocation.

3) Visual estimates of the percentages of the different categories of gravel sizes were made at each site along the profile where the elevation readings were made.

4) Detailed photographs were taken.

5) Where surface oil was present, visual estimates of the surface coverage were made. Notes were made as to the thickness and character of the surface oil.

6) Trenches were dug at several intervals along the profile to determine the depth of oil penetration. Each trench was described and photographed in detail.

7) Sediment samples were collected of surface and subsurface oil contamination. Surface samples, the top 2 centimeters (cm), were collected only for detailed characterization and analysis of weathering trends. Subsurface samples were collected from discreet 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. All samples from a station were numbered sequentially, with the surface samples designated 'A' and the subsurface samples designated 'B.' Samples were collected with clean scoops and placed in pre-cleaned glass jars with teflon-lined caps.

Thirty-one sediment samples were collected and kept frozen onboard the vessel during the survey, then shipped in coolers to the Institute for Environmental Studies, LSU. The gravimetric method, after solvent extraction with freon (Standard Method 503) was used on 27 samples to analyze for total petroleum hydrocarbons (TPH). Table 1 lists the TPH results for all samples.

analyze for total petroleum hydrocarbons (TPH). Table 1 lists the TPH results for all samples.

Table 1. TPH in mg/kg for sediment samples collected in August 1991.

Sample No. (mg/kg)	Depth (cm)	Zone*	Visual Oil Description	TPH
N1/1B	35-45	Upper	OF	2,010
2B	35-55	Mid	MOR	820
3B	65-75	Mid	HOR	12,580
4B	40-70	Mid	MOR/LOR	5,160
N3/1B	42-52	Mid	MOR	4,670
2B	52-64	Mid	HOR	12,520
3B	40-45	Mid	HOR	9,210
N4/1B	25-35	Mid	MOR	
N5/1A	0-3	Upper	AP	4,930
N5/2A	0-3	Upper	No Oil	N/A
N6/1B	0-10	Upper	MOR	32,000
2B	5-10	Mid	HOR	27,850
N7/1B	30-55	Upper	LOR	6,510
2B	25-45	Mid	MOR	9,370
3B	35-45	Mid	MOR	6,480
4B	65-75	Mid	MOR+	14,750
N10/1B	35-38	Upper	No Oil	260
2B	5-10	Mid	MOR	4,660
N11/1B	5-12	Upper	LOR	140
2B	0-5	Upper	LOR	920
3B	10-15	Mid	Peat	1,500
N12/1A	0-3	Upper	SOR	26,000
N13/1B	15-20	Upper	MOR+	5,500
2B	10-15	Mid	MOR	<100
N15/1B	25-50	Upper	LOR	3,160
2B	35-45	Mid	LOR	32,000
3B	55-60	Mid	MOR	
N17/1B	20-30	Mid	OF	1,060
N18/1B	30-45	Mid/Lower	LOR	20
2B	0-15	Mid/Lower	MOR	5,500
3B	35-45	Lower		

* Zone - Relative position along the intertidal zone.

More detailed chemical characterization by gas chromotography/mass spectrometer (GC/MS) was done on 13 selected samples. Targeted for analysis of the weathering patterns of the residual oil were 37 polynuclear aromatic hydrocarbon (PAHs). The results for the August 1991 samples are included in the Appendix. Throughout the discussion of hydrocarbon weathering, the PAH patterns are plotted normalized to the individual PAH that has the highest concentrations. This approach facilitates comparison of the relative distribution of PAHs among samples that vary widely in concentration. The emphasis is on comparisons of the change in the relative amount of PAHs.

Throughout the text, we have used the terminology and definitions established during the 1991 interagency shoreline surveys, May Shoreline Assessment Program. Surface oil was described using the following terms:

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

Coat (CT): Oil that ranges between 0.1 and 1.0 mm thick (can be easily scratched off with 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 residue, but not generally flowing out of sediments.

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

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

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

Chapter 2

RESULTS AND DISCUSSION OF STATION SURVEYS

Cobble-Boulder Platforms with Berms (Heavily Armored)

Introduction

Six of the stations revisited during this survey were originally classified as cobble-boulder platforms with berms (Michel and Hayes, 1991). These areas have been of special concern during the response to the *Exxon Valdez* spill because oil had penetrated below a stable armor that occurs on all gravel beaches of this class in PWS. The middle and lower portions of the intertidal zones of these beaches are typically gently sloping surfaces of bedrock covered by a veneer (armor) of cobbles and boulders. The upper part of the beach profile usually contains a high, generally supratidal, storm berm, usually composed of cobbles, which has a series of mobile berms composed of pebbles and cobbles on its seaward face. These lower-level berms occur within the upper intertidal zone. All these types of beaches are limited to the segments of the PWS shoreline most exposed to storm-wave action. The beaches in this class resurveyed during the August 1991 survey included station N-1 at Point Helen, stations N-3 and N-4 on Smith Island, station N-7 on Knight Island, station N-17 on Perry Island, and station N-15 on Latouche Island (Figure 1).

Station N-1 (Point Helen)

There are two sites at Point Helen that our team has studied: station N-1, located about 1.5 kilometers (km) north of the south end of the island and about 200 meters (m) north of a prominent raised sea stack; and a berm relocation site at KN-405A, located about 600m north of the south end of the island (Figure 2). The survey conducted at station N-1 on 21 August 1991 was the tenth such survey since the first one in September 1989. This station is located on one of the most exposed sites in PWS; consequently, it contains very coarse sediments that show signs of significant transport by wave action, namely rounding and sorting of the individual clasts. The berm relocation site at KN-405A was visited three times by members of the NOAA geomorphology team: on January 23, 1991, June 4, 1991, and August 27, 1991. Despite its location on a section of Point Helen, which is highly exposed to wave action, a 45- by 22-meter (m) zone of residual oil remained in the upper intertidal zone as late as June 1991 (see field sketch in Figure 3).

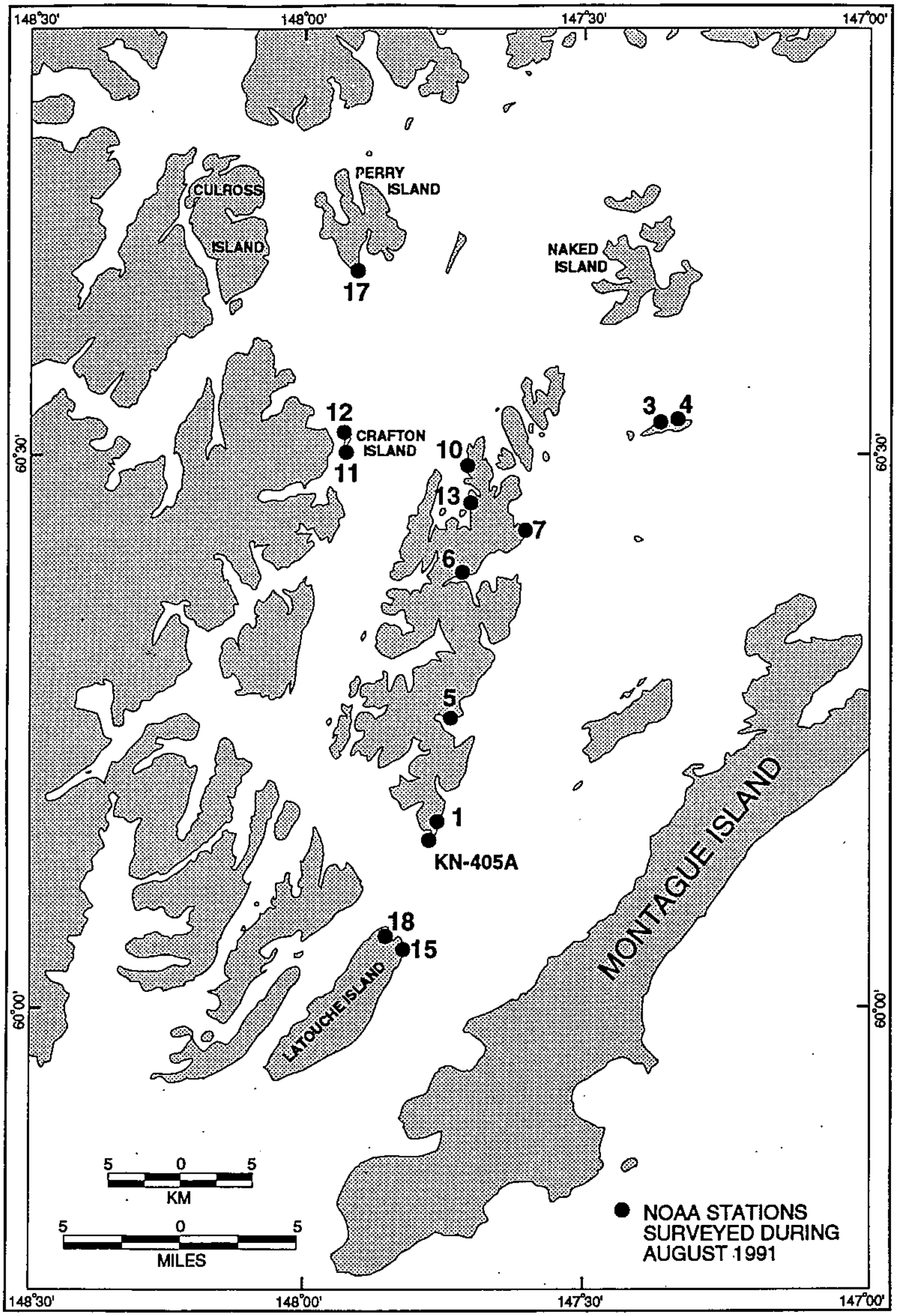


Figure 1. Location of the sites surveyed during the August 1991 study.

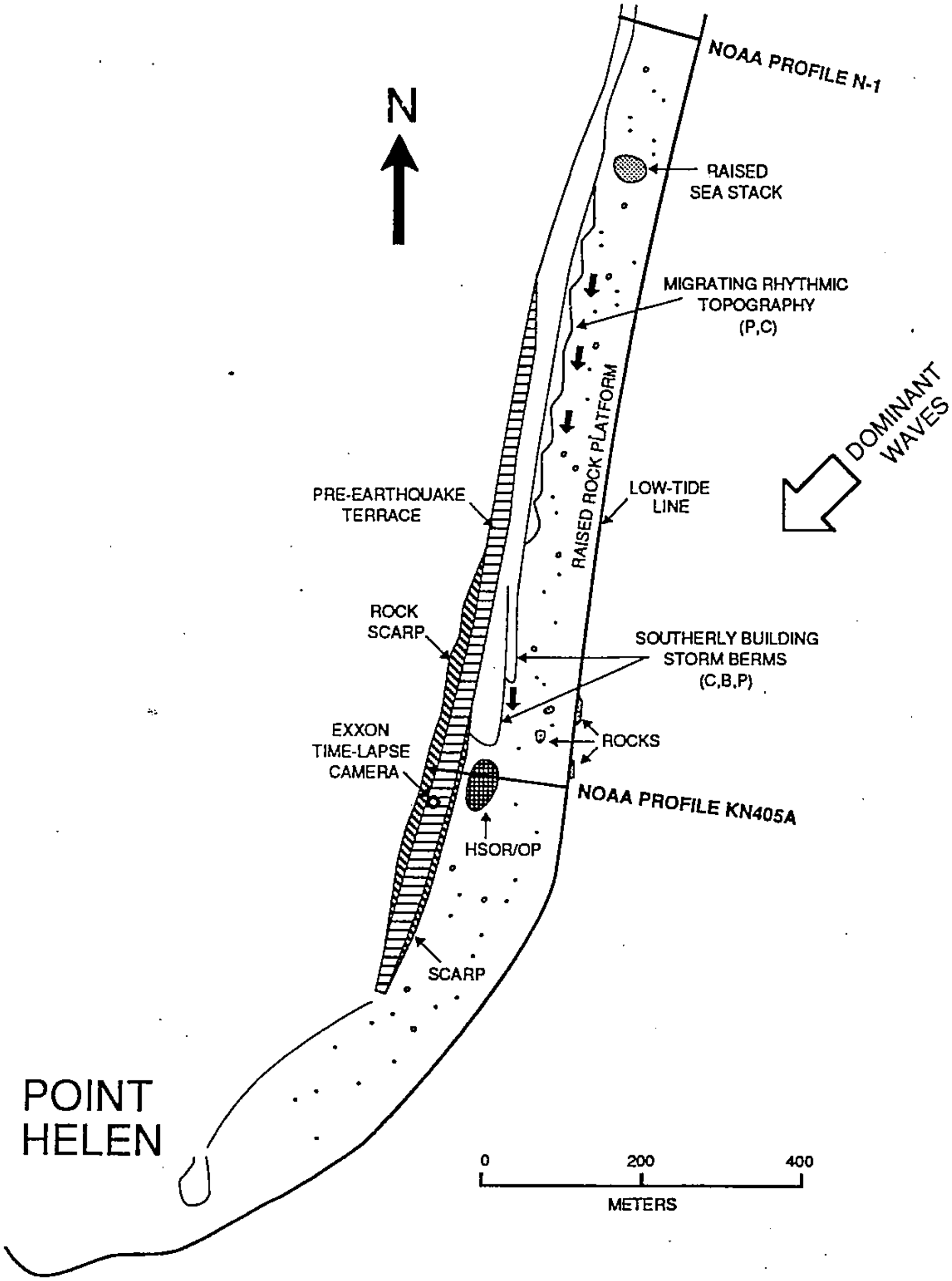


Figure 2. Sketch map of the Point Helen area, showing the zone of residual oil present in June 1991. Map is based on both the MAYSAP field survey of April 27, 1991, and observations made during a visit by a TAG-initiated team on June 4, 1991.

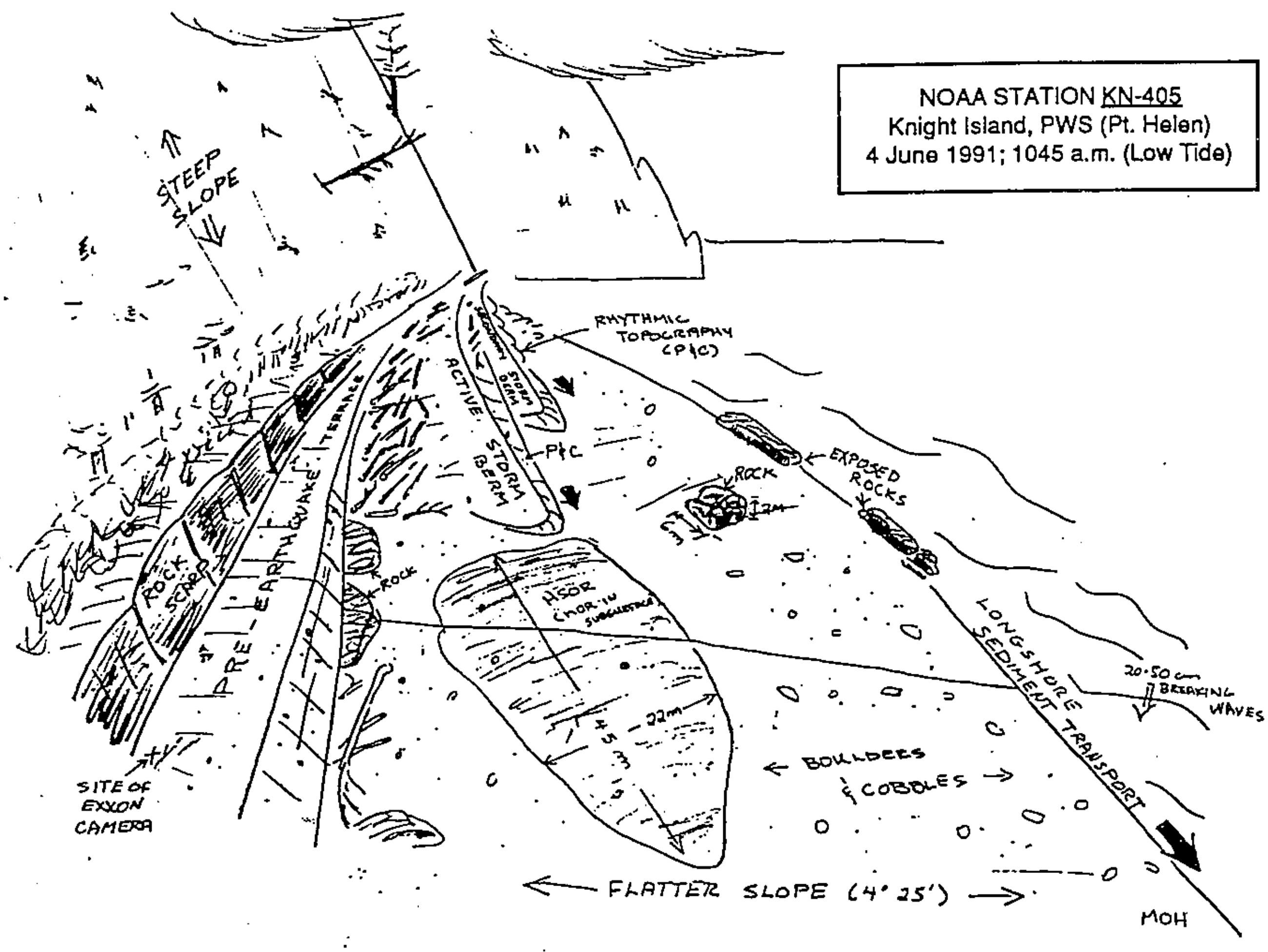


Figure 3. Field sketch of berm relocation site KN-405A on June 4, 1991. Note protection from wave action afforded to the zone of oil persistence by both: a) the southerly prograding storm berms, and b) the rock outcrops in the intertidal zone.

The persistence of the zone of residual oil at KN-405A was puzzling because much of this stretch of coast had undergone considerable cleaning by wave action and hydraulic flushing since the oil spill. As shown by our field survey of the site on January 23, 1991, however, there were some notable differences between this site and NOAA's station N-1:

1) Much greater content of surface and subsurface oil.

2) Flatter slope (4.5 degrees as opposed to 6 degrees at station N-1; Figure 4).

3) No storm berm per se. Instead, there is an eroded scarp in a pre-earthquake gravel deposit (Figure 3).

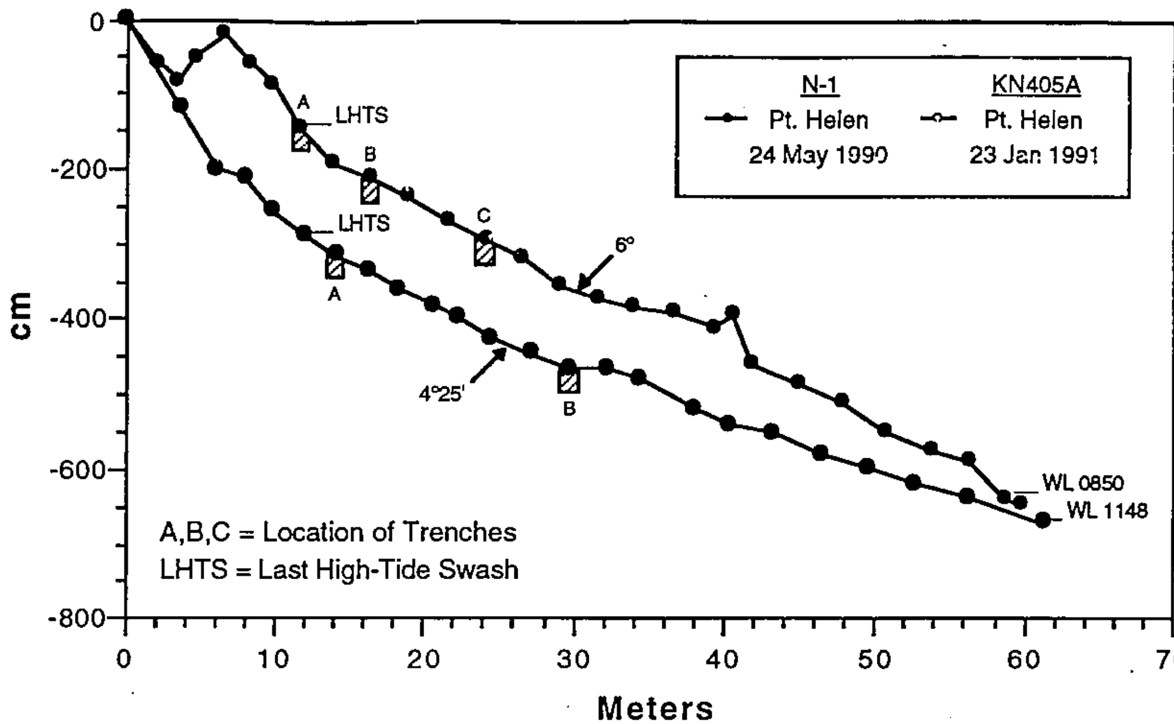


Figure 4. Comparison of NOAA's station N-1 with the area where the oil-accumulation zone was located in June 1991 (KN-405A). Note flatter average slope and absence of storm berm at KN-405A.

There are several lines of geomorphic evidence that indicate that the dominant wave approach direction along Point Helen is east to northeast, with a resulting dominant longshore sediment transport direction from north to south:

1) Field observations at station N-1 during the non-summer months of 1989-90 revealed the presence of numerous oblique gravel bars (swash bars) in the intertidal zone that were moving south.

2) Grain size and shape trends in the sediments.

3) Southerly prograding storm berms and rhythmic topography (Figures 2 and 3).

Observations recorded in the Exxon time-lapse photography and wind data recorded at the meteorological stations on Danger and Seal islands support these observations. A more limited fetch in a southeasterly direction and the sheltering effect of Montague Island, also contribute to the wave and sediment transport patterns observed at Point Helen.

After studying KN-405A and other available data, we concluded that two major factors were responsible for the presence of the residual oil patch at that site:

1) It is sheltered from the dominant wave approach direction; and

2) There are lower rates of hydraulic flushing at this site than at cleaner areas, such as at NOAA's station N-1.

It was clear from Exxon's time-lapse photography than the storm waves during the winter of 1990-91 broke on a line of rocks near the low-tide line, a major single rock in the intertidal zone, and other rock outcrops nearby. More important than the rock outcrops, however, was the sheltering effect of a major storm berm that was built out on the raised rock platform a few meters north of the oil accumulation zone (Figures 2 and 3). These elements combined to produce a tombolo-effect, or sheltering (Michel and Hayes, 1991), of the area where the oil remained. It is conceivable, as well, that this effect allowed for heavier-than-normal oil accumulation in the sheltered area during the spill, as was suggested during a TAG meeting in Anchorage in June.

Our studies at station N-1 revealed significant decreases of subsurface oil over time, even below the zone of reworking by wave action. We have concluded that the relatively steep slope of the rock platform (6 degrees), the relative thinness of the gravel veneer over the rock platform, and the lack of sediments finer than pebbles in the subsurface sediments of the upper platform enhanced hydraulic flushing of subsurface oil at that station (Hayes et al., 1990). The average slope of the platform at the oil-accumulation site at KN-405A is considerably less and the subsurface sediments are finer. Therefore, we conclude that hydraulic flushing was not as effective in removing the subsurface oil at this location as it was as station N-1.

When we returned to KN-405A on August 27, 1991, the zone of residual oil discussed above had been mechanically removed. Furthermore, a major berm relocation project had been carried out for the entire length of Point Helen, including at the site of NOAA's station N-1.

Needless to say, the berm relocation at station N-1 had a profound effect on the resultant topographic beach profile measured on August 27, 1991. This profile is compared with the survey of January 23, 1991, in Figure 5. The most conspicuous effect of the berm relocation was the planing of the storm berm and dispersal of the gravel over the landward surface of the upper platform. This modification of the storm berm is illustrated in the two photographs in Figure 6 and the field sketch in Figure 7.

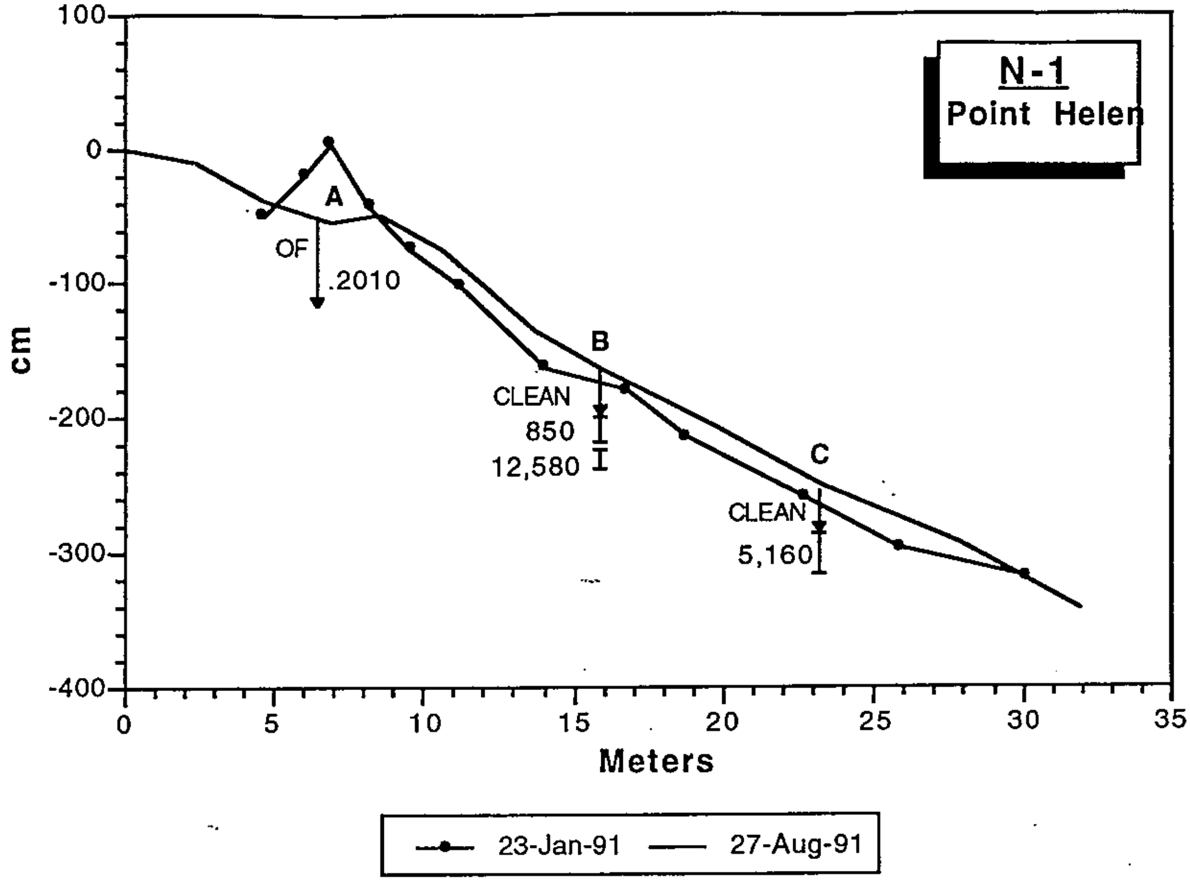


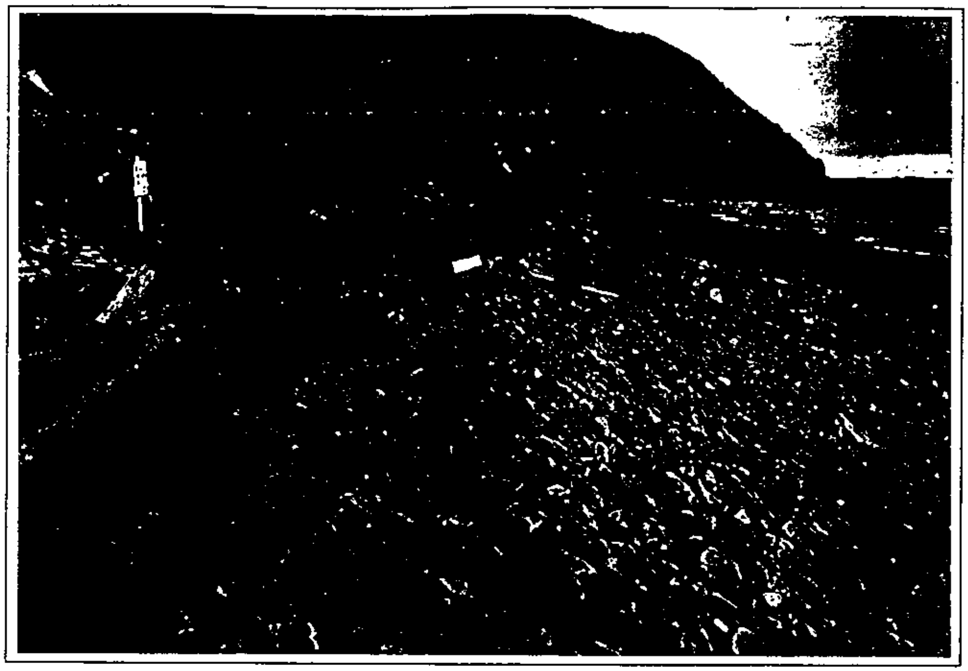
Figure 5. Comparison of the beach profile at station N-1 on August 27, 1991 with the survey conducted on January 23, 1991. The conspicuous gravel storm berm present in January was planed off and pushed seaward during the berm relocation process carried out in July. Note the presence of OF on the cobbles and pebbles in the subsurface of the area previously occupied by the storm berm (trench A). The two trenches dug further down the profile (trenches B and C), had clean surface sediments.

Figure 6. (Facing Page) Modification of the storm berm at station N-1 by the berm relocation process.

(A) Northerly view on October 20, 1989. Note well-developed crest on the storm berm. Photo by D. Hall.

(B) Same view on August 27, 1991, showing the planed off storm berm and the disarray of logs behind the beach as a result of the berm relocation. Photo by M. Hayes.

A.



B.

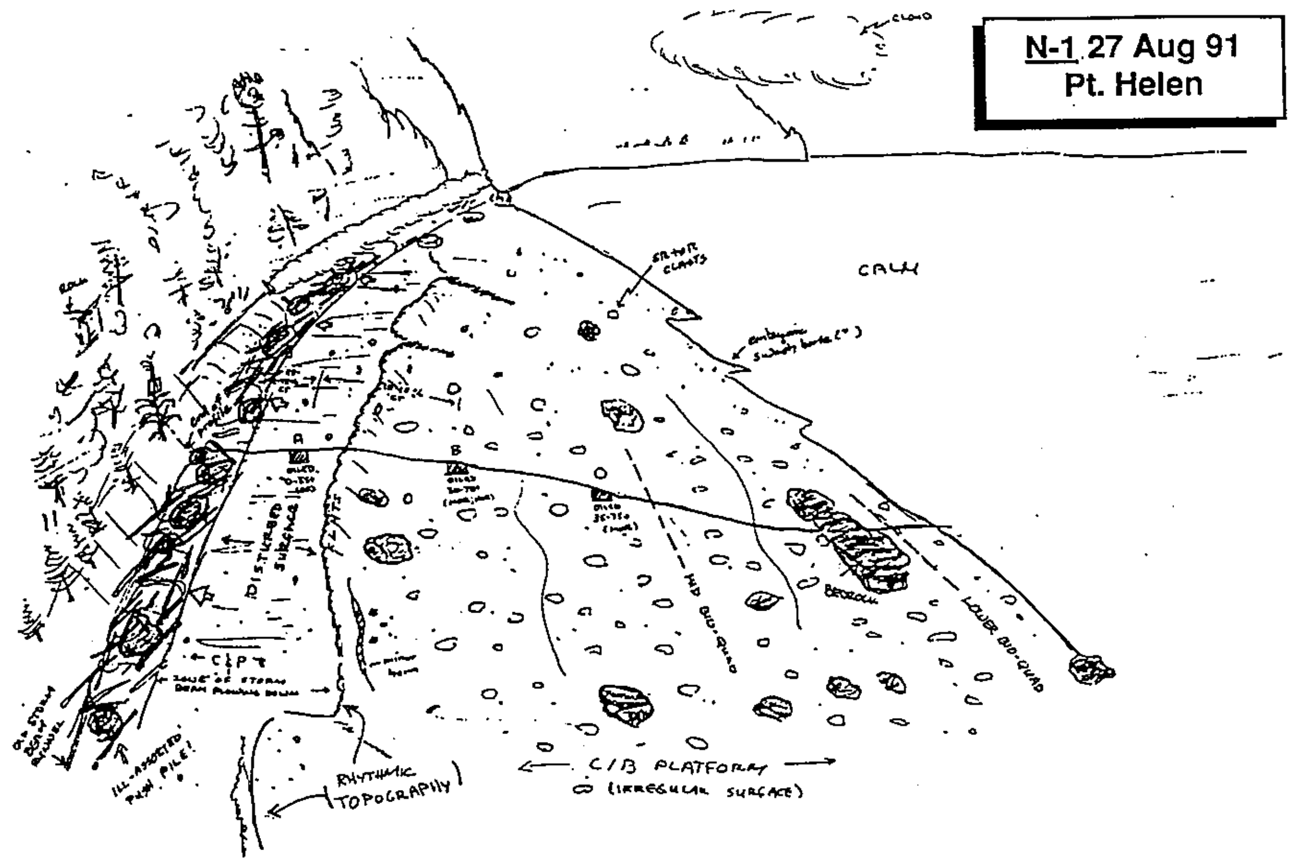


Figure 7. Field sketch of station N-1 on August 27, 1991. Note presence of oil coated (CT) pebbles and cobbles near the planed off storm berm.

Because of the exposure of this beach to relatively heavy wave action, no significant surface oil had been observed at this station since the September 1990 survey. Therefore, the oiled cobbles and pebbles exposed at this site by the berm relocation process should be cleaned before the end of the next storm season. However, as shown by the trends in the degree of sediment contamination in Figure 8, reported as TPH in mg/kg, the deeper subsurface oil of the upper platform remains relatively unchanged as far as oil volumes are concerned. On the other hand, it is important to note that the depth to the subsurface oil has gradually increased over time, to the extent that the armor on the surface of the upper platform is now completely clean. This trend in the reduction of the subsurface oil "from the top down" is clearly illustrated by comparing the trenches dug at the station on May 24, 1990, with those dug on August 27, 1991, (Figure 9). Also note the disruption of the armor at trench A by the berm-relocation process.

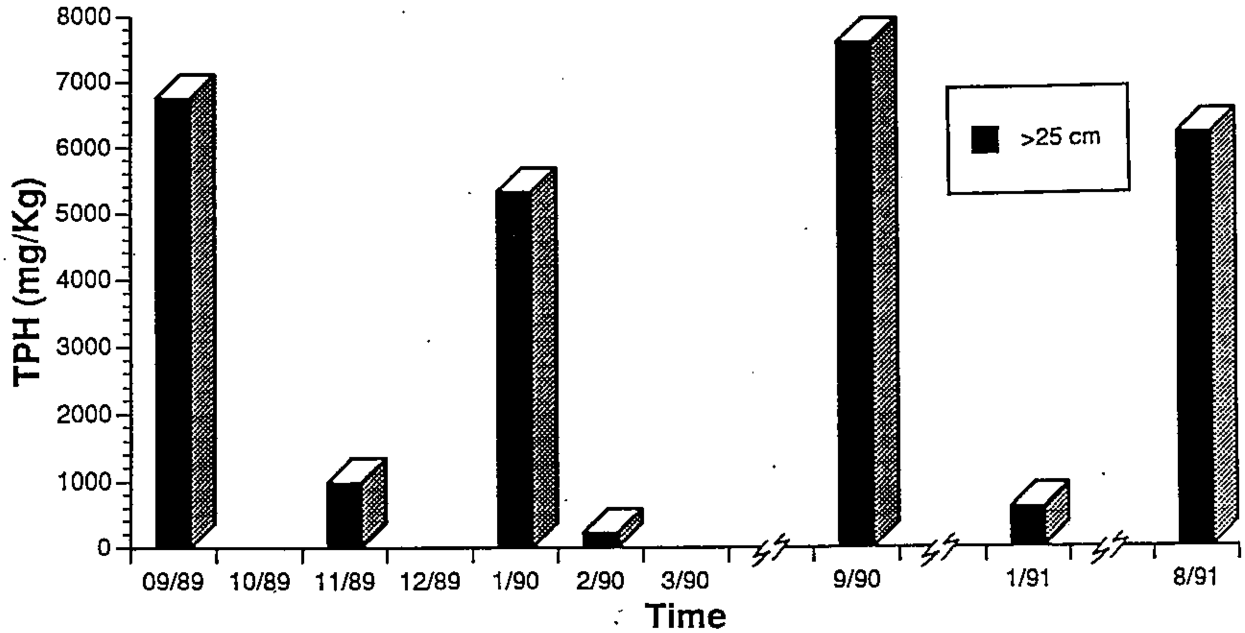


Figure 8. TPH data for the subsurface sediment samples from the upper platform (trenches B and C; Figures 5 and 9). The August 1991 value is the average of two samples from trench B and one sample from trench C (Figure 5).

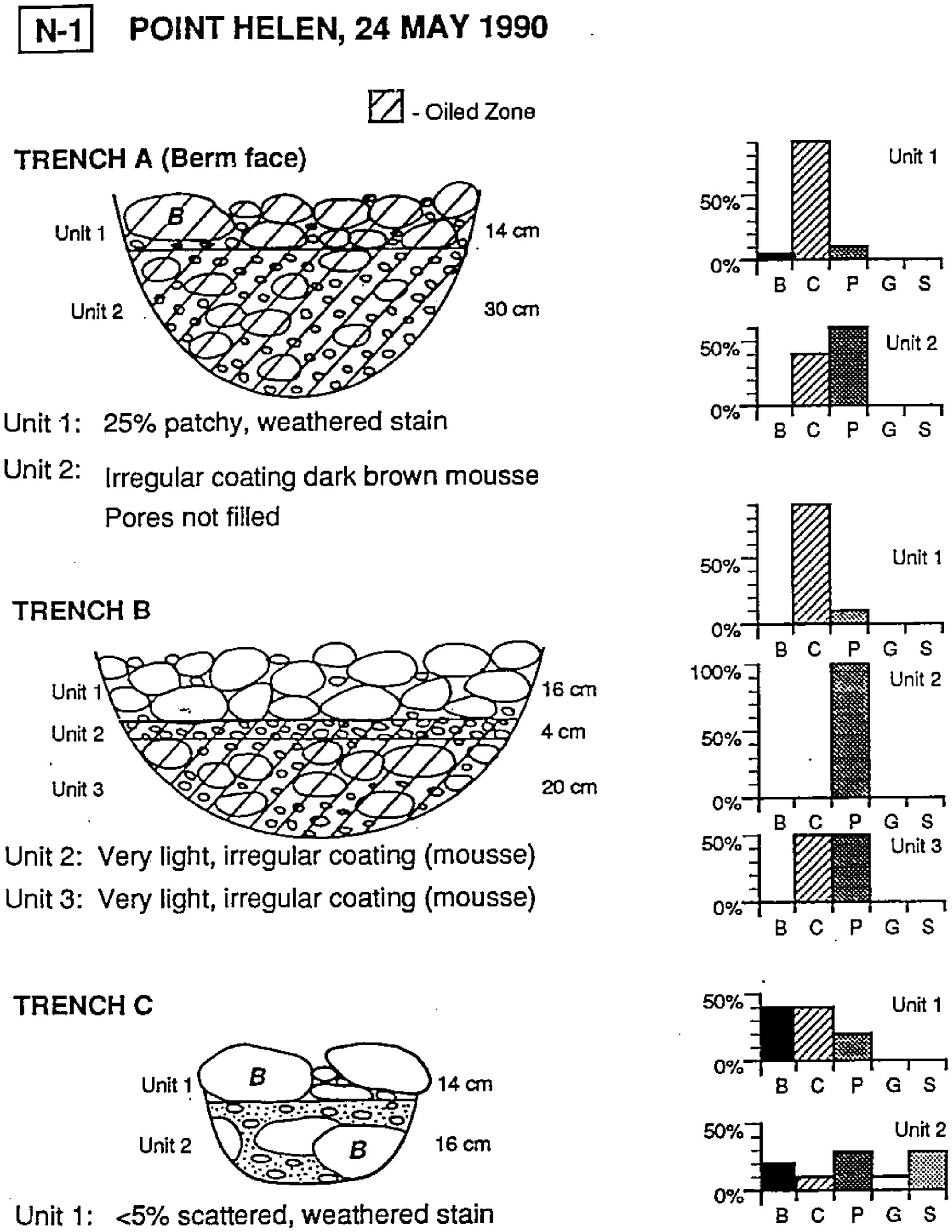
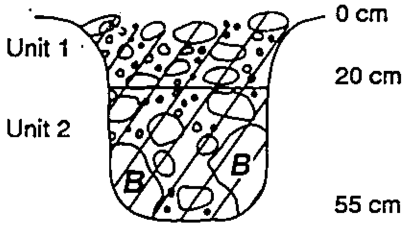


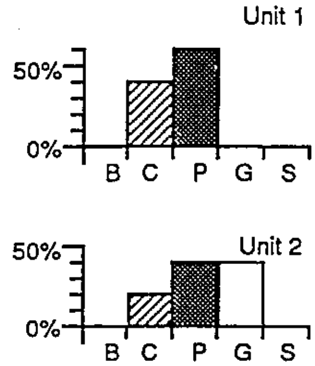
Figure 9. Changes of subsurface oil and sediment patterns at station N-1. Trenches A and B dug during the survey of 24 May 1990 (located on Figure 4). Note the tendency for the upper units to be coarser grained than the lower units, a result of the armoring process. Also note that the upper sediments in the trenches are relatively free of oil as a result of wave action during the non-summer months of 1989 and 1990.

N-1 POINT HELEN, 27 August 1991

- Oiled Zone

TRENCH A

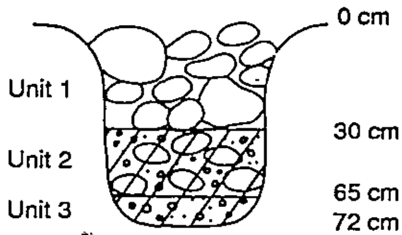


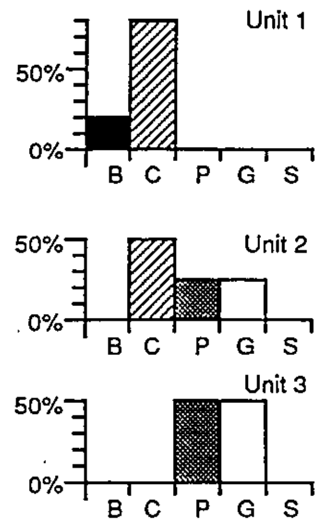


Unit 1: Relocated berm area. Oil on surface and with depth as black stain/ coat.

Unit 2: Brown oil film on all clasts. Not clean below. Sampled 35-45cm (1B).

TRENCH B



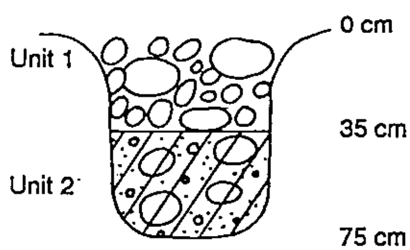


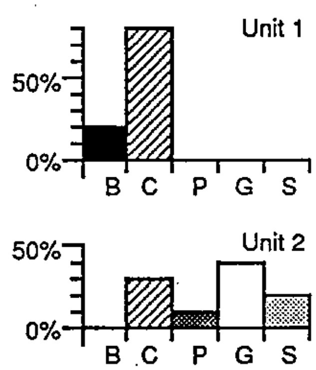
Unit 1: Light stain on cobble armor.

Unit 2: Moderate oil residue. Sampled 35-55cm (2B).

Unit 3: Heavy oil residue in pebble/ granule sediments. Not clean below. Sampled 65-72cm (3B).

TRENCH C





Unit 1: Clean armor.

Unit 2: Lightly oiled throughout with a band of MOR at 45-55cm. sampled 40-70cm (4B).

Figure 9. (continued) Trenches A, B, and C dug during the survey of August 27, 1991 (Figure 5). Note that the top of the subsurface oil was considerably deeper during the August 1991 survey than during the May 1990 survey (30 to 35 cm compared to 16 cm). Also note the destruction of armoring in trench A by the berm relocation process.

Station N-3 (Smith Island)

This station, which has been surveyed ten times since the first survey in September 1989, is located in a small indention on the northwest side of Smith Island. The beach is oriented east-west and is exposed for a distance of 45 to 50 km in a north-northeast direction making it one of the most exposed beaches in PWS.

Except for an erosional event between January 30 and March 4, 1990, that lowered the whole profile about 40 cm, this beach has remained quite stable throughout the study period as far as natural processes are concerned. However, a berm-relocation project was carried out at the site in mid-July 1990, during which the seaward face of the storm berm was excavated 0.5 to 1.0 m, and the excavated sediment was placed on top of the upper platform. The impact of the berm relocation on the topography of profile N-3 is shown in Figure 10A. Note that the crest of the storm berm was not changed in the relocation process. The displaced sediment was returned quickly to its original position by wave action during the early months of the 1990-91 storm season, as is shown by the profile run on January 21, 1991, (Figure 10B). As indicated by the profile plot for August 26, 1991, (Figure 10C), however, the beach changed very little after that with respect to its topography.

The grain-size estimates made along the profile during the surveys of May 25, 1990, September 7, 1990, and August 26, 1991, given in Figure 11, show that the surface grain-size pattern along the profile had returned to its original configuration within one year. The photograph in Figure 12A shows the upper part of the beach in late August 1991.

Figure 10. (Facing Page) Changes of the beach profile at station N-3.

A. Plots of the May 25, 1990, and September 7, 1990 profiles. The effect of the berm relocation project carried out at this site in mid-July 1990 is clearly shown. The face of the storm berm was excavated to a depth of 0.5m, and the excavated sediment was placed on the upper platform.

B. Plots of the September 7, 1990, and January 21, 1991, profiles. The profile had returned to its original configuration by the January survey.

C. Plots of the January 21, and August 26 1991, profiles. Very little change took place during this interval.

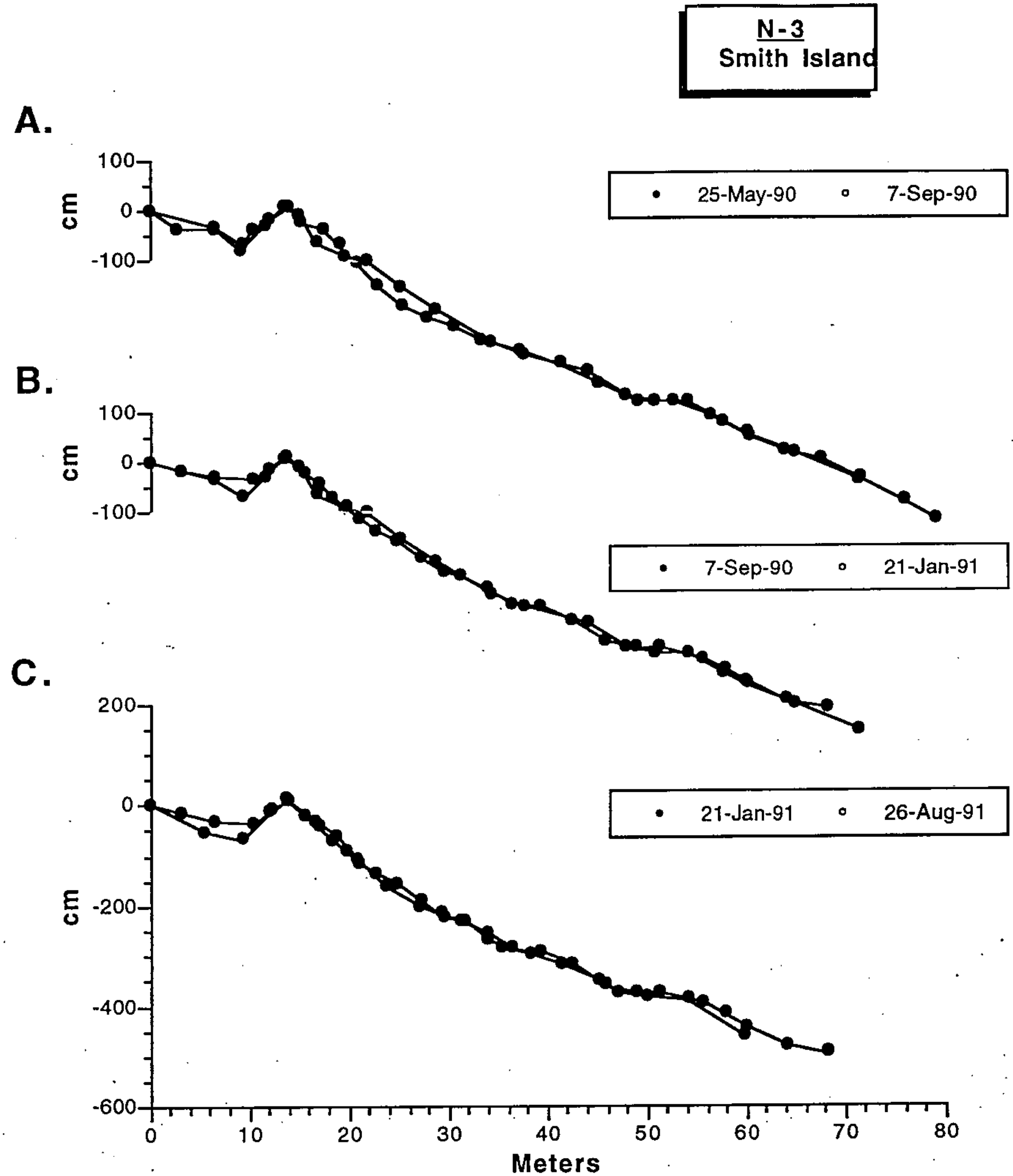
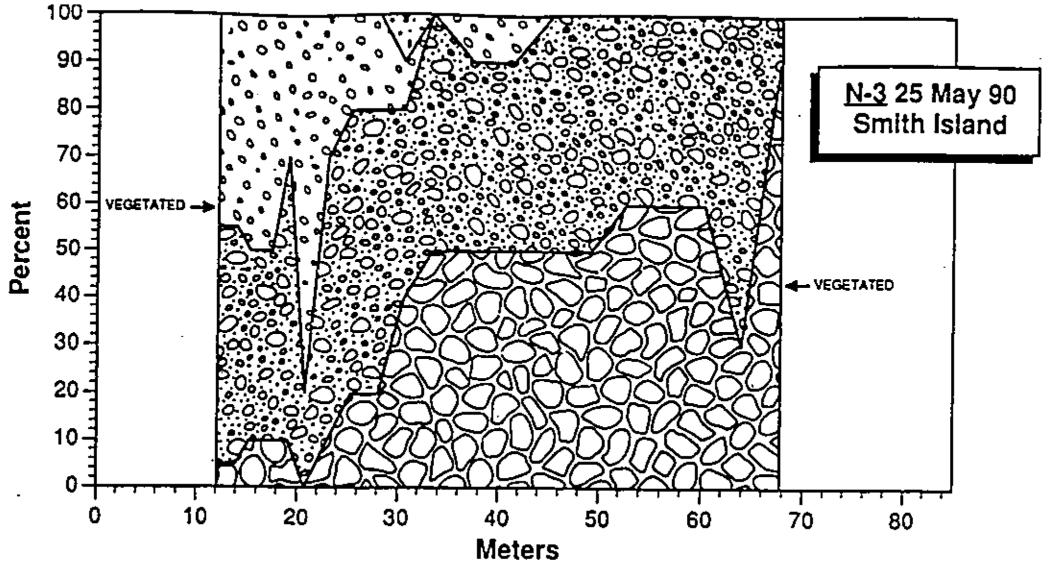
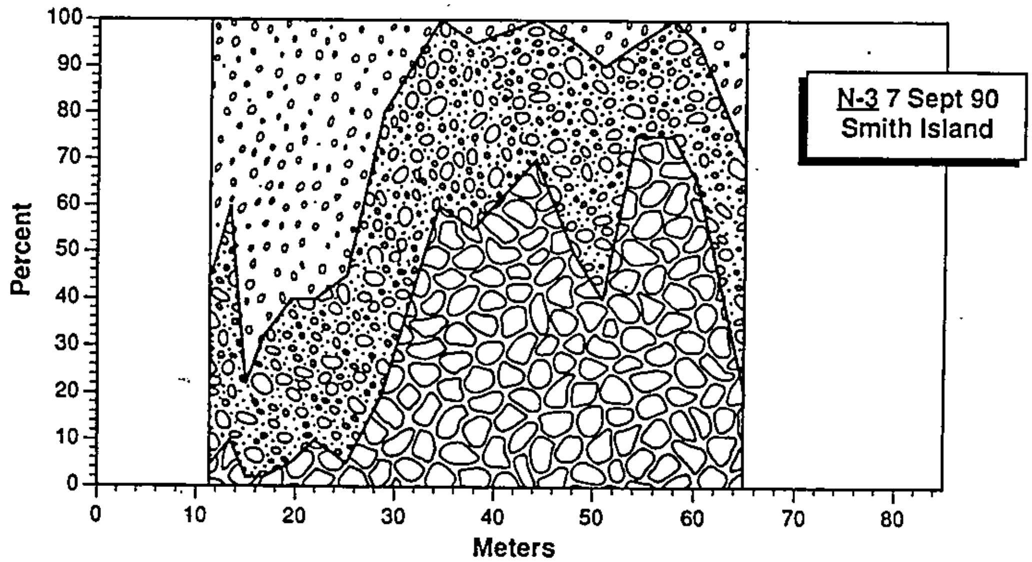
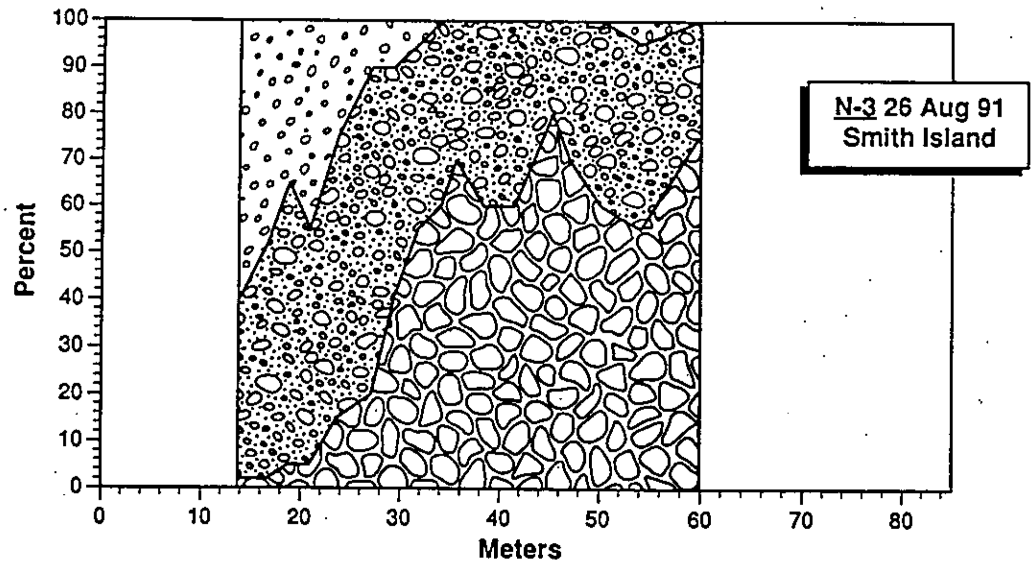

N-3
Smith Island
A.
B.
C.
25-May-90
7-Sep-90
7-Sep-90
21-Jan-91
21-Jan-91
26-Aug-91
cm
Meters
100
0
-100
200
-200
-400
-600
10
20
30
40
50
60
70
80

Figure 11. (Facing Page) Plots of visual estimates of the grain size of surface sediments along profile N-3 made during the surveys conducted on May 25, 1990, September 7, 1990, and August 26, 1991. Note that the surface sediments had returned to their original texture by the time of the August 26, 1991 survey. Pebbles were much more widely distributed over the surface of the beach immediately after the berm relocation project was completed in mid-July 1990 (see plot for September 7).







Boulder Cobble Pebble Granule

Figure 12. (Facing Page) Photographs of station N-3 on August 26, 1991.

A. Westerly view of the high-tide zone of the beach, showing the recovered high-tide berm area. Also note the disoriented logs. Photo by M. Hayes.

B. Trench C (see Figure 13 for location). Note oil on water at bottom of trench. Photo by J. Michel.

A.

B.

This station, as well as most the rest of the north shore of Smith Island, was heavily impacted by oil during the early days of the spill. Most of the beaches were treated by a wide range of methods. As noted earlier (Michel and Hayes, 1991), the rate of removal of surface oil at this site has been slow compared to station N-1. As late as May 1990, there was 5 to 20 percent stain on the surface cobbles. An asphalt pavement was exposed on the upper platform during the May 25, 1990, survey; and, subsurface oil has remained relatively high throughout the study (Figures 13 and 14). The oil that was formerly present in the subsurface in the lower units of trenches B and C on the upper platform (Figures 13 and 14) has been significantly reduced. The surface armor was clean at trench B, but there was a light oil residue all the way to the surface in trench C. The trench descriptions made during the August 1991 survey are compared with those of the May 1990 survey in Figure 15. This comparison illustrates the effectiveness of the berm relocation to enhance the removal of the subsurface oil in the high-tide berm area, and the continued persistence of high amounts of subsurface oil under the armor of the upper platform on this high-energy gravel beach (for PWS). TPH values ranging from 4,500 to 12,500 mg/kg were obtained for three samples of the subsurface sediments collected during the August 1991 survey.

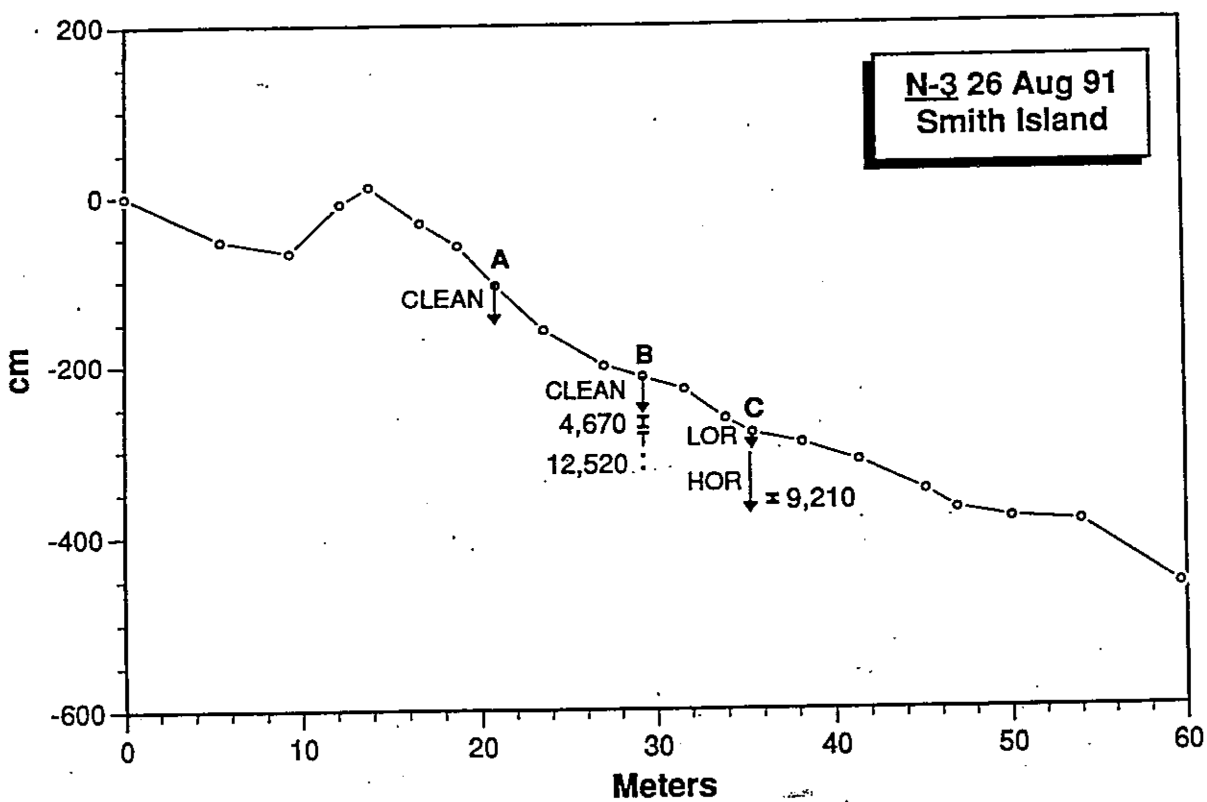


Figure 13. Topographic beach profile for station N-3 measured on August 26, 1991, showing location of trenches dug on the profile, as well as oiling of subsurface sediments in the three trenches.

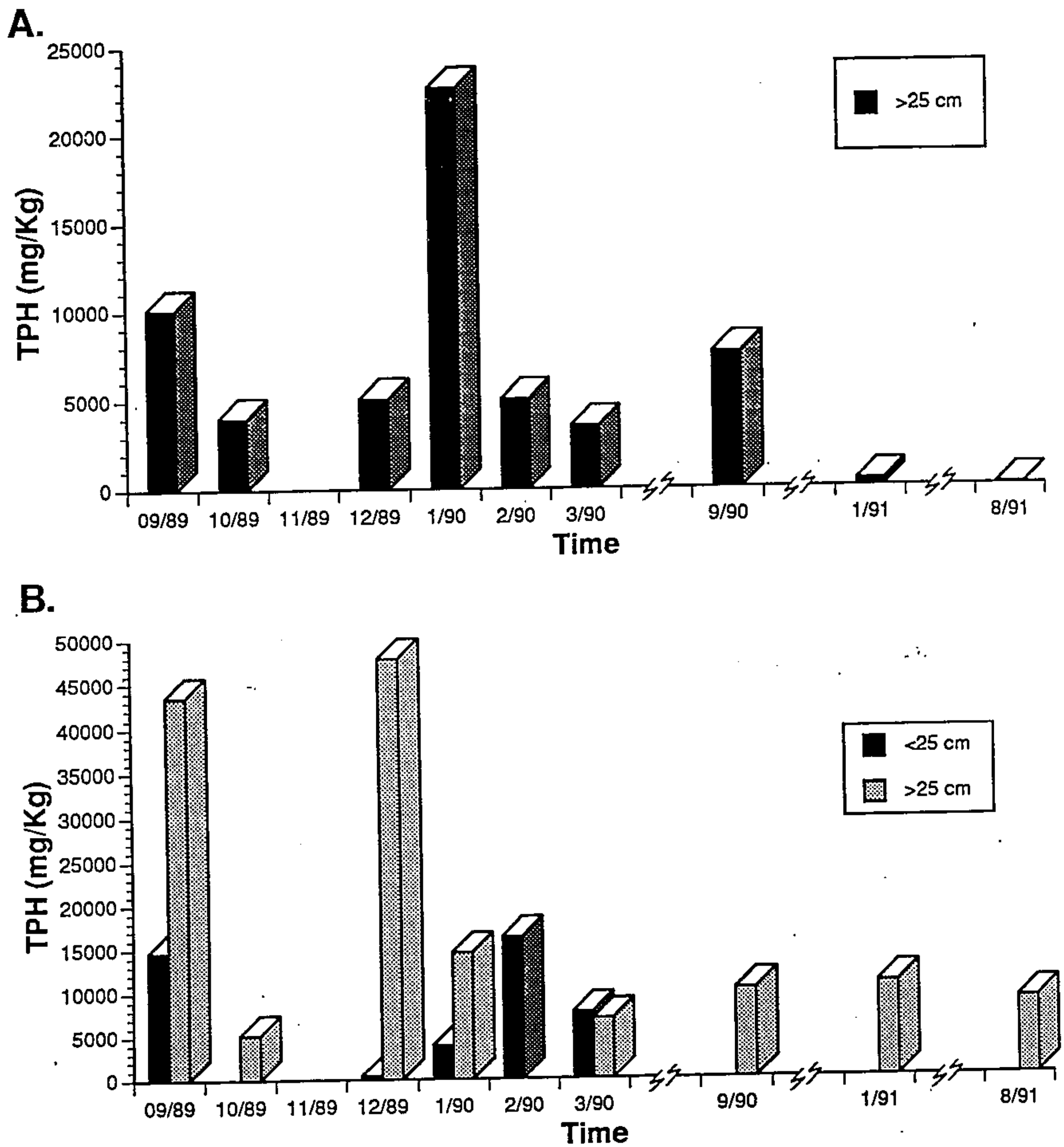


Figure 14. TPH data for station N-3.

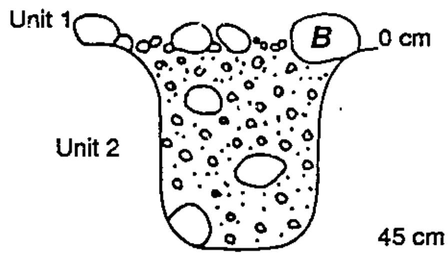
A. Changes in subsurface oil concentrations along the high-tide berm. Note the disappearance of subsurface oil at this site following the berm-relocation project of mid-July 1990.

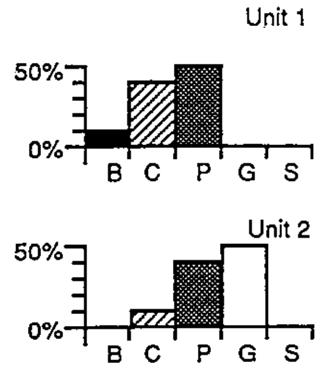
B. Changes in subsurface oil concentrations over time for the upper platform area (trenches B and C). Note the persistence of the subsurface oil in this area.

N-3 SMITH ISLAND, 26 August 1991

- Oiled Zone

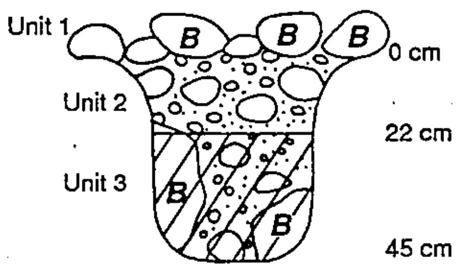
TRENCH A

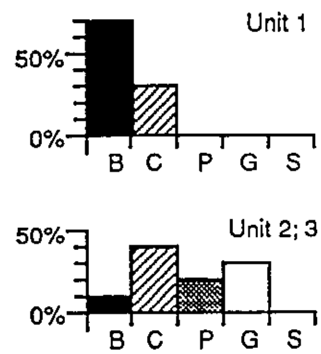




Unit 1: Surface armor. No oil.
Unit 2: No oil.

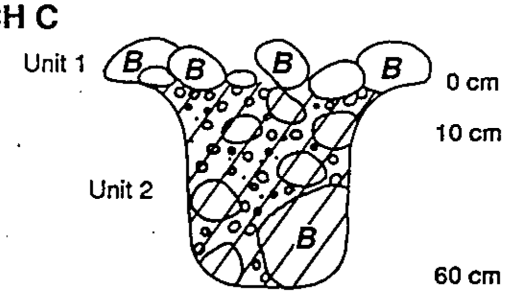
TRENCH B

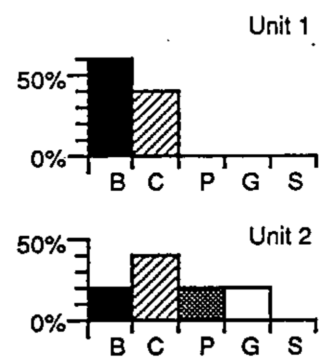




Unit 1: Boulder armor; 20cm thick.
Unit 2: No oil.
Unit 3: Moderately oiled (MOR) 22-32cm (sample 1B). Heavily oiled 32-45cm (sample 2B).

TRENCH C





Unit 1: Surface boulder armor.
Unit 2: Oily film 0-10cm. Heavy oil 10-40cm (HOR). Not clean below. Sampled 40 - 45cm (3B). Black oil slick on water table.

Figure 15. Comparison of the trench descriptions for station N-3 for the surveys done in May 1990 and August 1991. Trenches described on August 26, 1991. Note that the high-tide berm trench (A) was clean, but that oil remained under the armor of trenches B and C, located on the upper platform. Compare trench C description with photograph in Figure 12B.

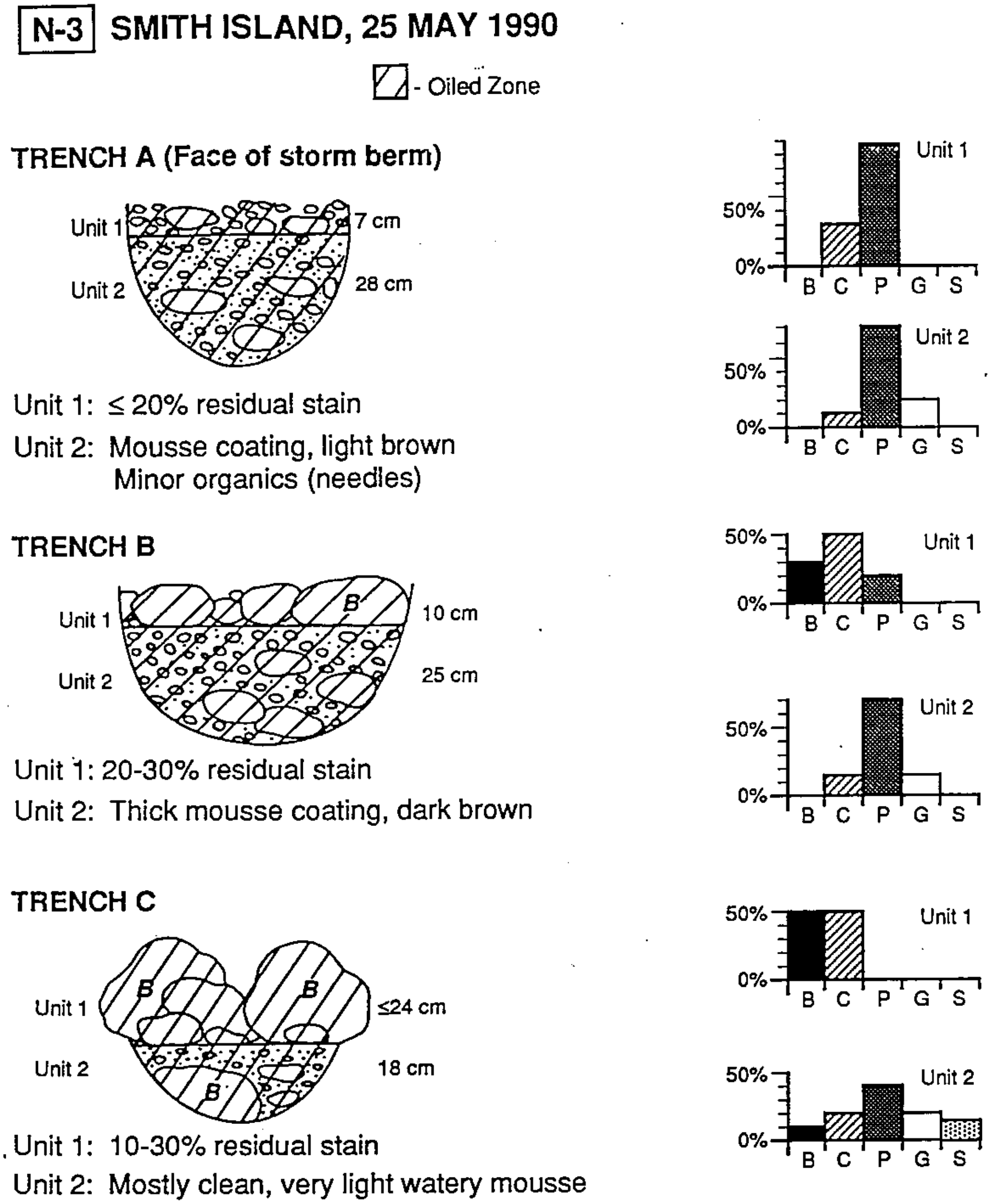


Figure 15. (continued).

Trenches described on May 25, 1990. Note the presence of surface oil at the three locations, all of which had been removed by the time of the January 1991 survey. Trench C was not dug deep enough to reach the heavy subsurface oil encountered during the August 1991 survey. Also observe the well-developed armor in trenches B and C, which prohibits reworking the subsurface sediments by normal storm-wave action.

Station N-7 (Knight Island)

This station, which was surveyed for the ninth time on August 27, 1991, was one of the 1990 test sites for monitoring of the effectiveness of bioremediation on subsurface oil (Customblen only application). Our profile line was the boundary between the fertilized (to the north) and unfertilized (to the south) halves of this pocket beach. It is one of the more sheltered stations classified as cobble-boulder platforms with berms in our study set. However, it shows excellent armoring all along the intertidal platform and its sediments are obviously reworked occasionally by large storms, as evidenced by the presence of a well-developed high storm berm. The beach profile has shown very few changes since the beginning of the study.

Throughout all the surveys, subsurface oil was consistently abundant at this station, as is shown in the TPH plot in Figure 16. There was a significant difference observed during the August 27, 1991 survey, however, in that the depth to the top of the subsurface oil, which had remained near the surface during the earlier surveys, was finally beginning to increase.

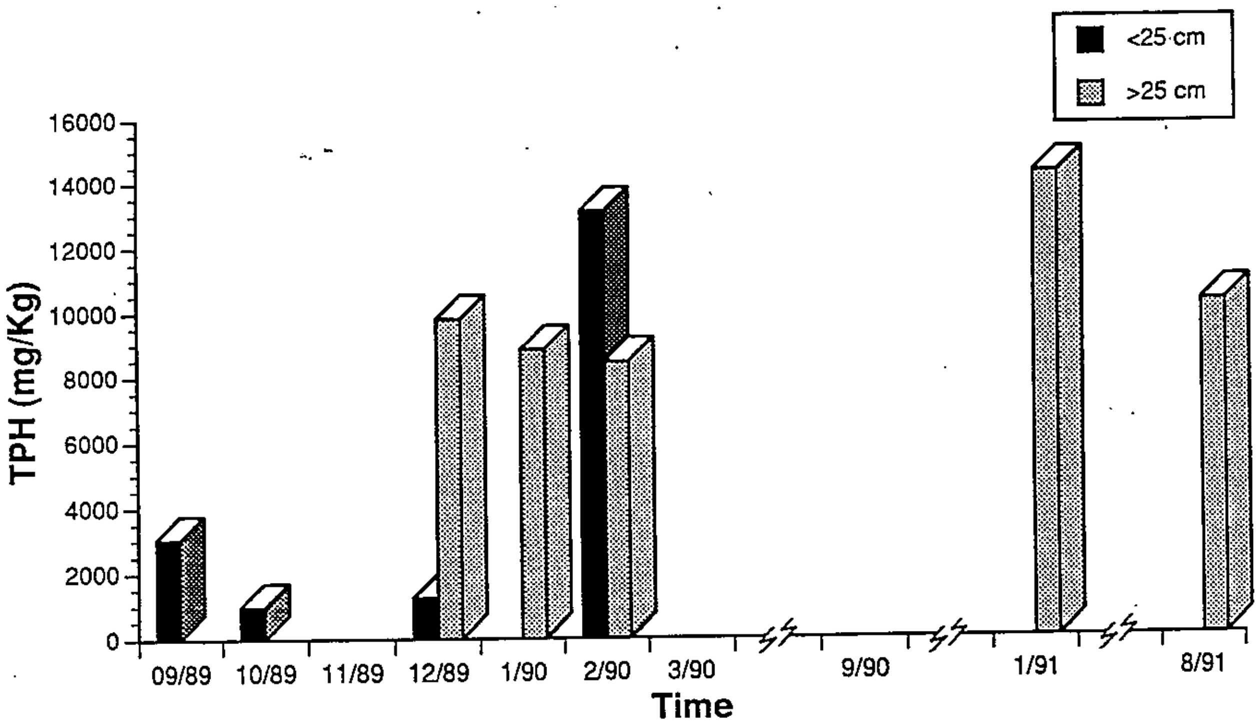


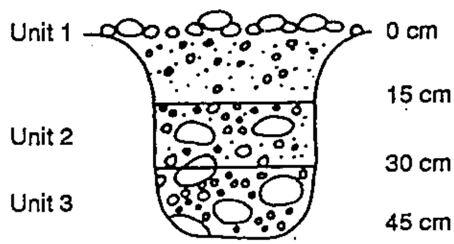
Figure 16. TPH data for the upper platform at N-7 over time. The deep subsurface oil at this station has showed little change since September 1989.

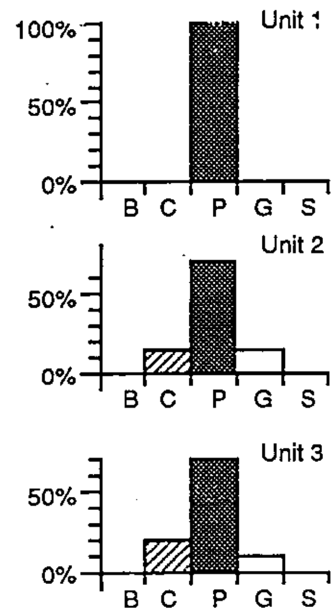
The sketches of the trenches dug during the August 1991 survey, shown in Figure 17, illustrate that depths to the top of the oil had increased to 30 cm in trench B, 10 cm in trench C, and 15 cm in trench D. Trench A was free of oil for the first time during the study.

N-7 KNIGHT ISLAND, 27 August 1991

- Oiled Zone

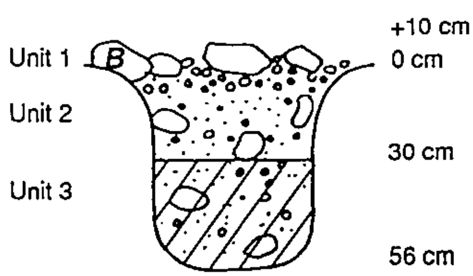
TRENCH A

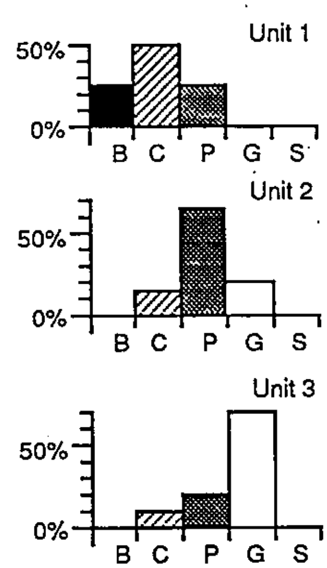




Unit 1: 100% smail pebbles.
Unit 2: Pebble/granule fraction very angular.
Unit 3: More cobbles, which are subrounded. No oil.

TRENCH B



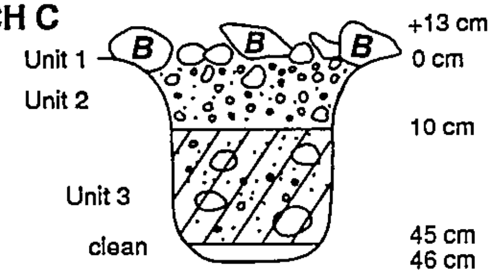


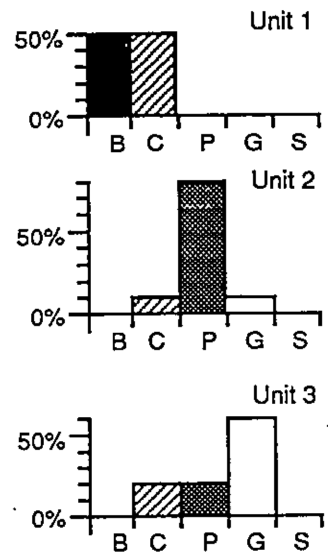
Unit 1: Surface armor, overlying pebble layer.
Unit 2: Clean zone.
Unit 3: Light/moderate oiling of granules. Sampled 30-56cm (1B).

Figure 17. Descriptions of the trenches dug at station N-7 on August 27, 1991. Note that trench A was free of oil, and that the upper portions of the sediments, including the well-developed armor, in all of the other trenches were free of oil, a marked change from the earlier surveys.

N-7 KNIGHT ISLAND, 27 August 1991

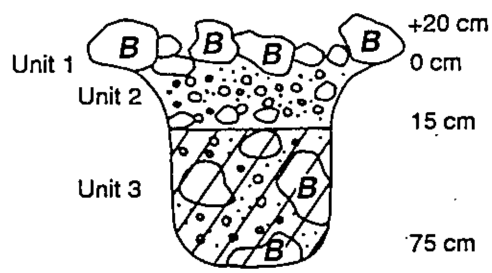
TRENCH C

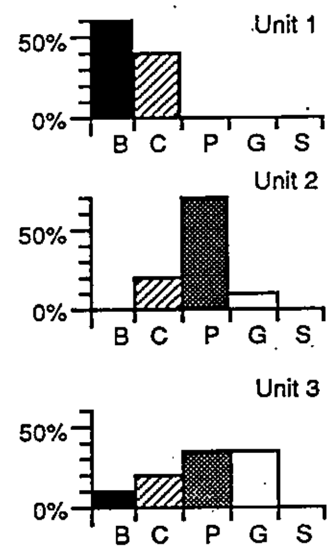




Unit 1: Surface armor.
Unit 2: Predominant pebble zone. No oil.
Unit 3: Moderately oiled zone of mostly granules. Sampled 25-45cm (2B). Clean below.

TRENCH D





Unit 1: Surface armor, 20cm thick.
Unit 2: No oil.
Unit 3: Moderately oiled zone, increasing oil content with depth, to 75 cm. Not clean below. Sampled 35-45cm (3B) and 65-75cm (4B).

Figure 17. (continued)

Station N-15 (Latouche Island)

This station is located in a pocket beach on the northeast corner of Latouche Island. Like the other stations in this class, it occupies a relatively exposed position, with an effective fetch of around 40 km. It has been surveyed ten times to date. Two additional profiles were established at the site during the June 25, 1990, survey and were resurveyed on August 28, 1991. The area was uplifted around 3.5 m during the Good Friday earthquake in 1964, the most of any of our permanent profiling sites. Unlike the previously discussed cobble-boulder platforms with berms stations, this pocket beach is underlain by a reddish fine-grained sediment rather than an uplifted bedrock platform. The well-rounded nature of the surface sediments indicates that wave energy is relatively high. The uplifted storm berm at this site is one of the largest in PWS. Interestingly, a large storm berm has not yet been rebuilt at this beach (since the uplift), presumably because of a paucity of available sediments.

This pocket beach was the site of a major berm relocation in early September 1990. As shown by the beach profile plots in Figure 18 and the photograph in Figure 19A, a +1.0-m-deep trench 10 to 15 m wide was dug down to the reddish fine sediment all along the location of the previous minor storm berm. The excavated sediment was piled on top of the upper platform, covering a zone about 25 m wide. The excavated pile of sediment shows up clearly on our profile plot of September 5, 1990, which was measured while the berm relocation project was in progress. According to an Exxon representative, after the exposed sediments were "tidally flushed," they were pushed back into their original position and Inipol/Custombien was applied.

Figure 18. (Facing Page) Comparison of beach profiles measured at station N-15.

- **A.** Plots of May 26 1990, and September 5, 1990 surveys, which illustrate the effect of the major berm-relocation project that was taking place when the survey of September 5 was done.
- **B.** Plots of September 5, 1990, and January 22, 1991, surveys. The excavated pile of sediments placed in the middle intertidal zone had been redistributed, but the excavated trench was not completely refilled.
- **C.** Plots of January 22, 1991, and August 28, 1991, surveys, which show little perceptible change.

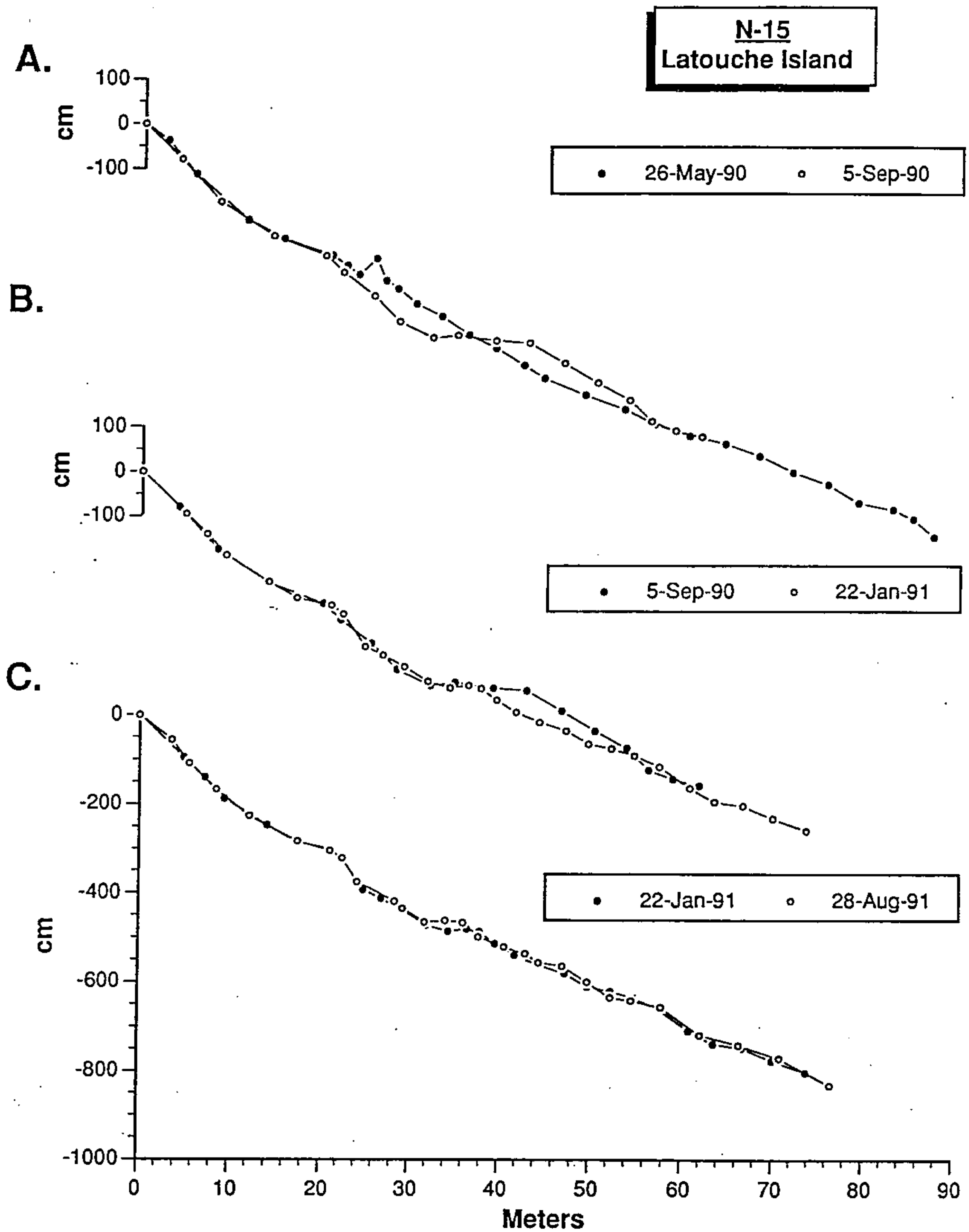
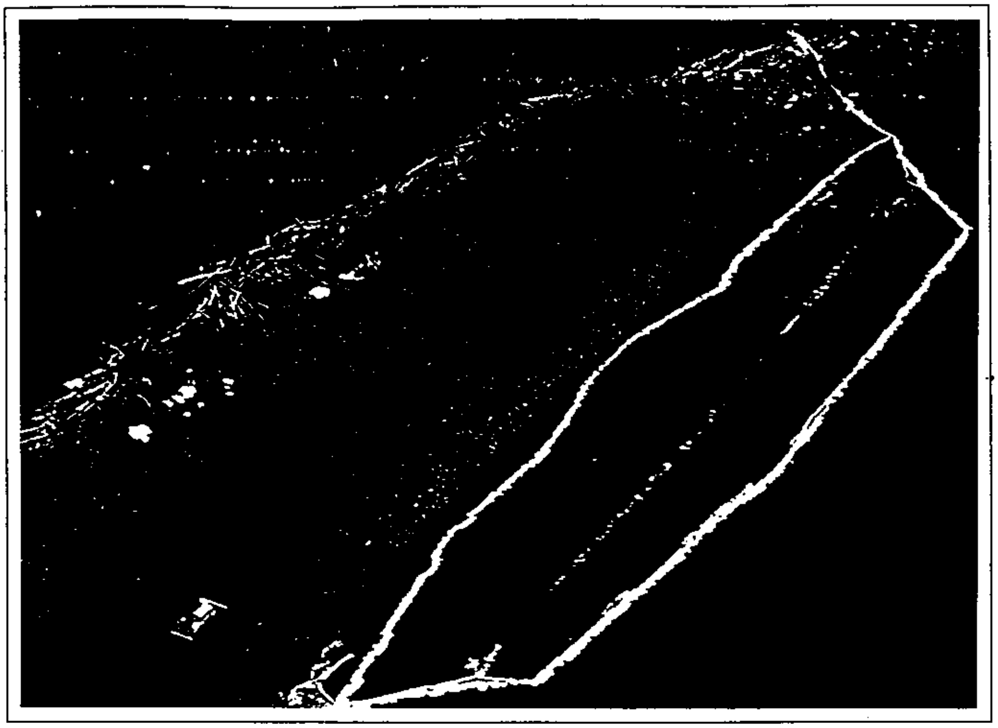

N-15
Latouche Island
A.
B.
C.
cm
100
0
-100
26-May-90
5-Sep-90
5-Sep-90
22-Jan-91
22-Jan-91
28-Aug-91
-200
-400
-600
-800
-1000
0
10
20
30
40
50
60
70
80
90
Meters

Figure 19. (Facing Page) Photographs at station N-15.

A. Northwest view on September 5, 1990. Berm relocation activities were in progress. Note abundance of exhumed oil. Photo by J. Michel.

B. Northwest view from spring high-tide berm on August 28, 1991. Note patchy surface oil in the middle distance (arrow). Photo by M. Hayes.

A.



B.

However, careful inspection of the beach profiles measured at station N-15 on January 22, 1991, and August 28, 1991, shows that the excavated trench has never been filled in, either by human or by natural processes. The excavated zone shows up clearly in the field sketch made during the August 28, 1991, survey (Figure 20). A patch of cobbles with 50 to 60 percent oil stain and coat was present on the surface of the excavated zone.

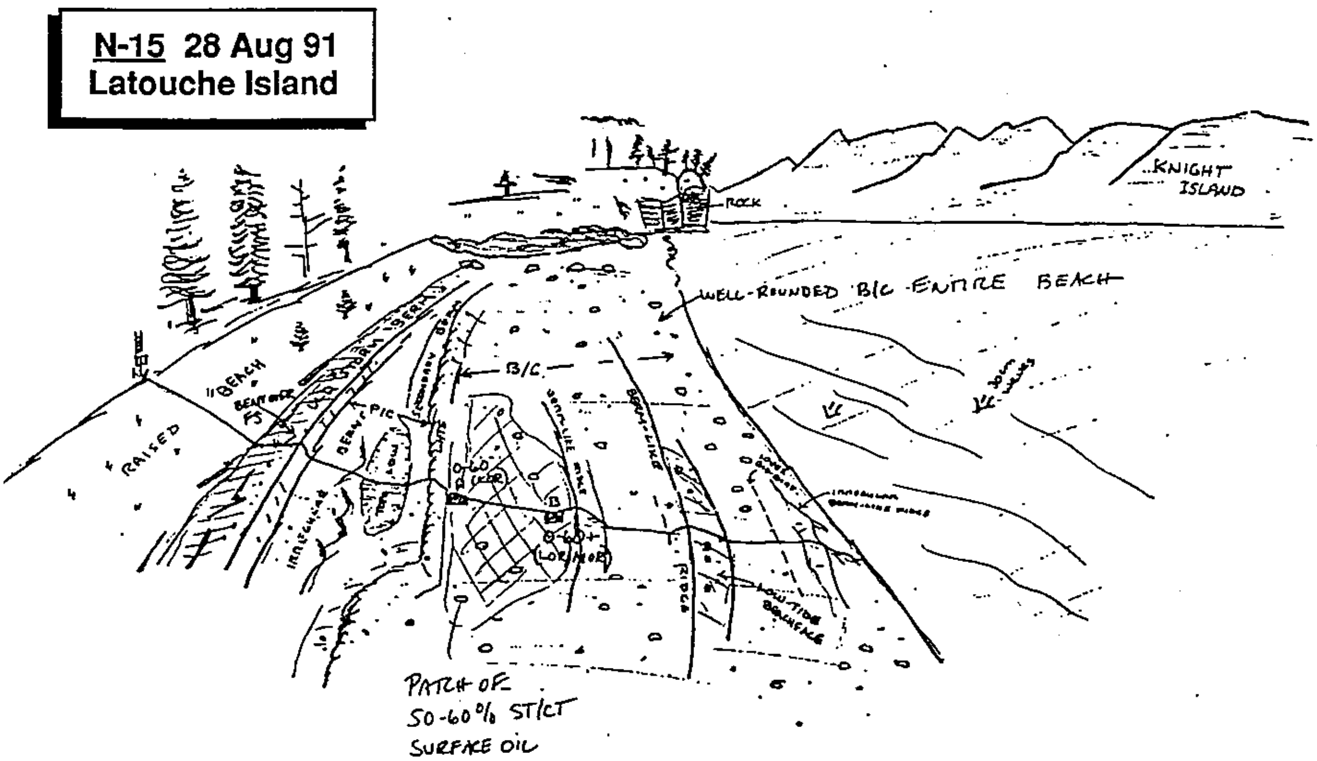


Figure 20. Field sketch of station N-15 on August 28, 1991. Note the topographically low area in the upper intertidal zone, which is at the location of the excavation trench created during the berm-relocation process.

It is puzzling why this profile took longer to recover than the other berm-relocation sites that our team studied. There are several interrelated probable causes:

1) The excavation was larger than the others we studied, and the sediment was piled further down the beach, making it more difficult for the waves to rebuild the natural profile.

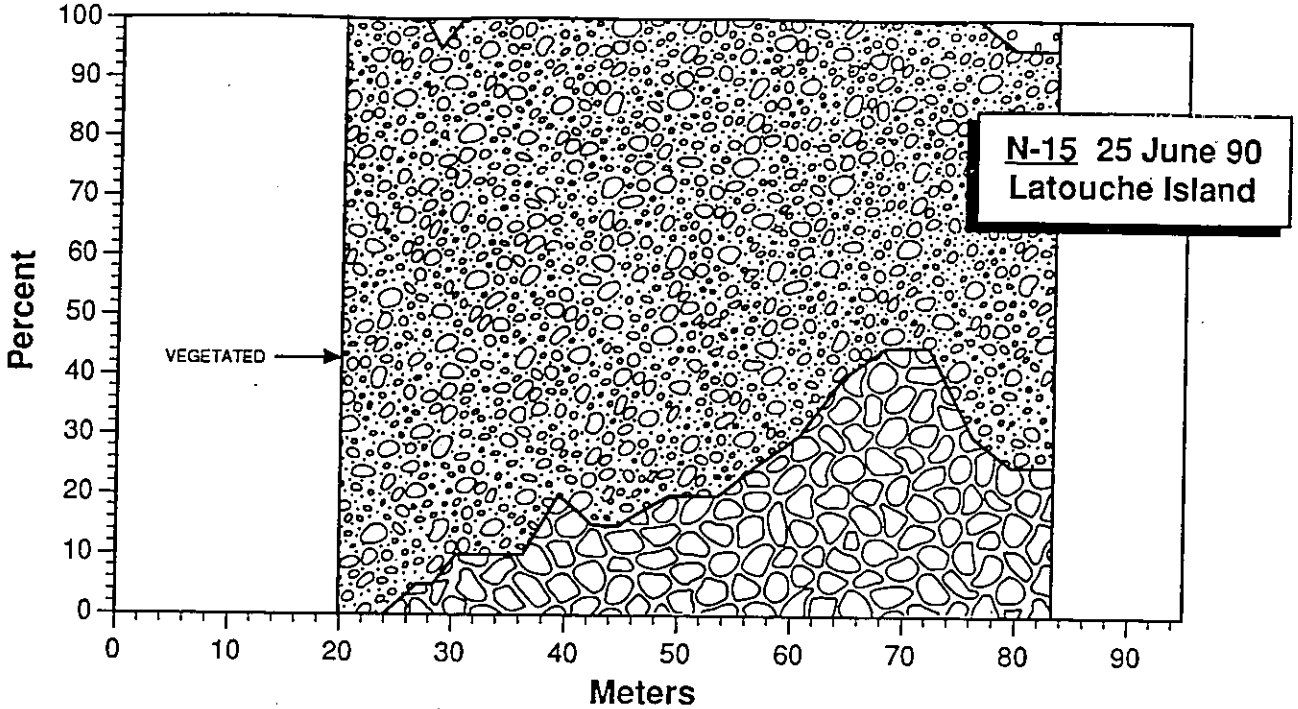
2) There is a well-documented, fairly strong northwest-southeast longshore transport within this pocket beach (Michel and Hayes, 1991). Therefore, it would appear that the sediment piled seaward of the excavation trench was transported laterally along the beach rather than back up the beach into the trench, as happened at most of the other berm-relocation sites. Note that the conspicuous sediment pile located on the middle platform during the September 5, 1990, survey was missing during the January 22, 1991, survey. We assume that the sediment was transported longshore towards the southeast.

3. It appears that most of the gravel on this beach is produced locally at the northwest end of the pocket beach. We hypothesize that there was not enough production of newly available sediment to replenish the sediments lost to the longshore transport system. The profile measured on August 28, 1991, was virtually the same as it was on January 22, 1991, (Figure 18C).

The surface sediments were also slow to return to their original distribution pattern after the berm relocation. The surface distribution on June 25, 1990, is compared with that of August 28, 1991, in Figure 21. The major difference is that the profile measured after the berm relocation contains a considerably larger pebble population, presumably because of the addition of pebbles derived from excavated sediments to the northwest by longshore sediment transport.

As shown by the field sketch in Figure 20 and the photograph in Figure 19B, there was a zone of surface oil, mostly coat and stain on pebbles and cobbles, present at the time of the August 28, 1991, survey. The persistence of stained cobbles on the surface over the 1990-91 storm season is markedly different from the 1989-90 storm season, when very heavily oiled surface cobbles were cleaned by March 1990. The berm-relocation project successfully removed subsurface oil. In 1991, subsurface oil was mostly light-to-moderate coating on all clasts, as compared to the pre-berm-relocation distribution of an oil-saturated zone of pebbles and granules below a cobble armor. Pre- and post-berm-relocation trenches are shown in the photographs in Figure 22. The trench descriptions for two trenches dug during the August 28, 1991, survey (Figure 23) illustrate the reduction in subsurface oil, as well as the disruption of the surface armor on the upper platform, by the berm-relocation process.

Figure 21. (Facing Page) Surface sediment distribution along the beach profile at station N-15 on June 25, 1990, (A) and August 28, 1991, (B). The surface sediments had not returned to their original configuration by August.


100
90
80
70
60
50
40
30
20
10
0
Percent
VEGETATED
N-15 25 June 90
Latouche Island
0
10
20
30
40
50
60
70
80
90
Meters

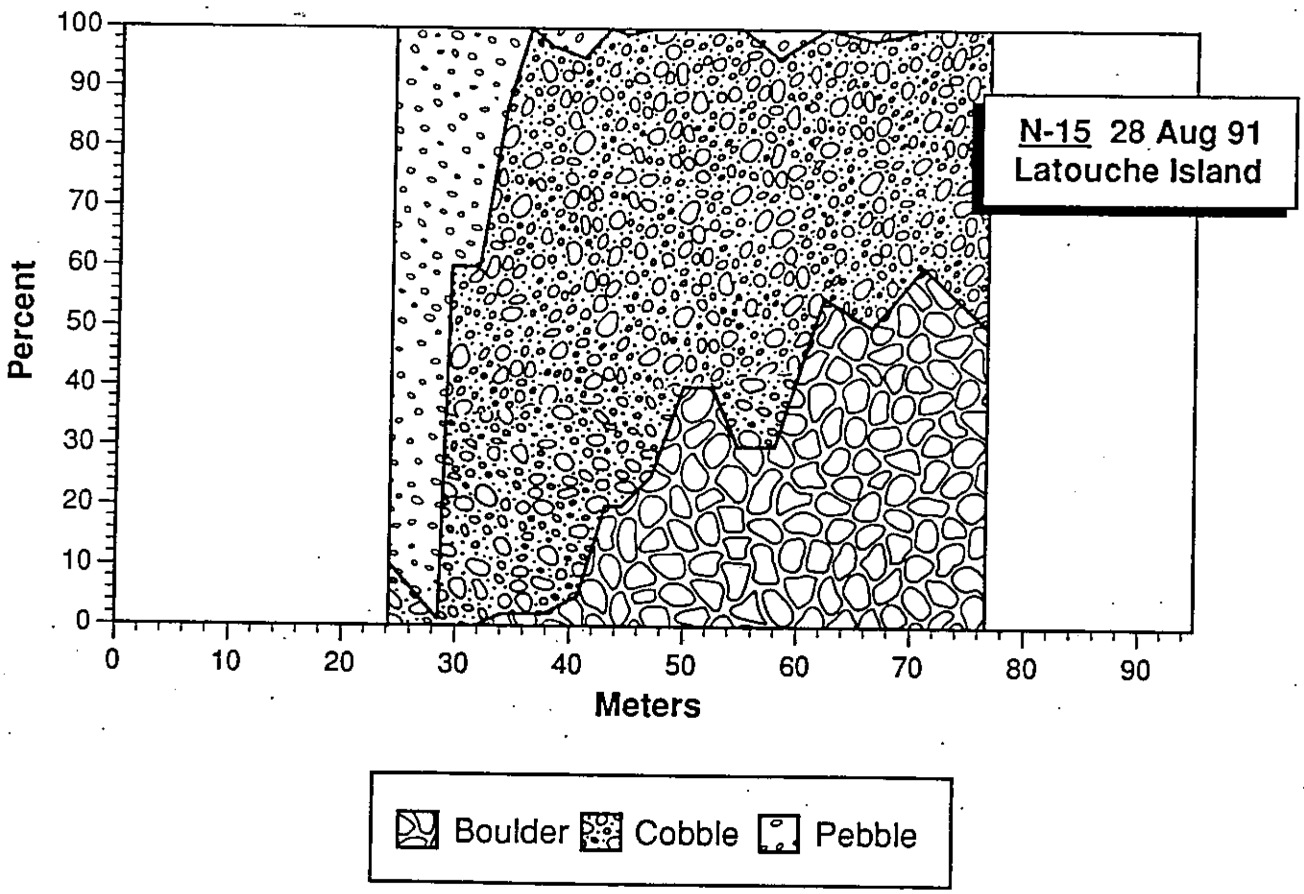
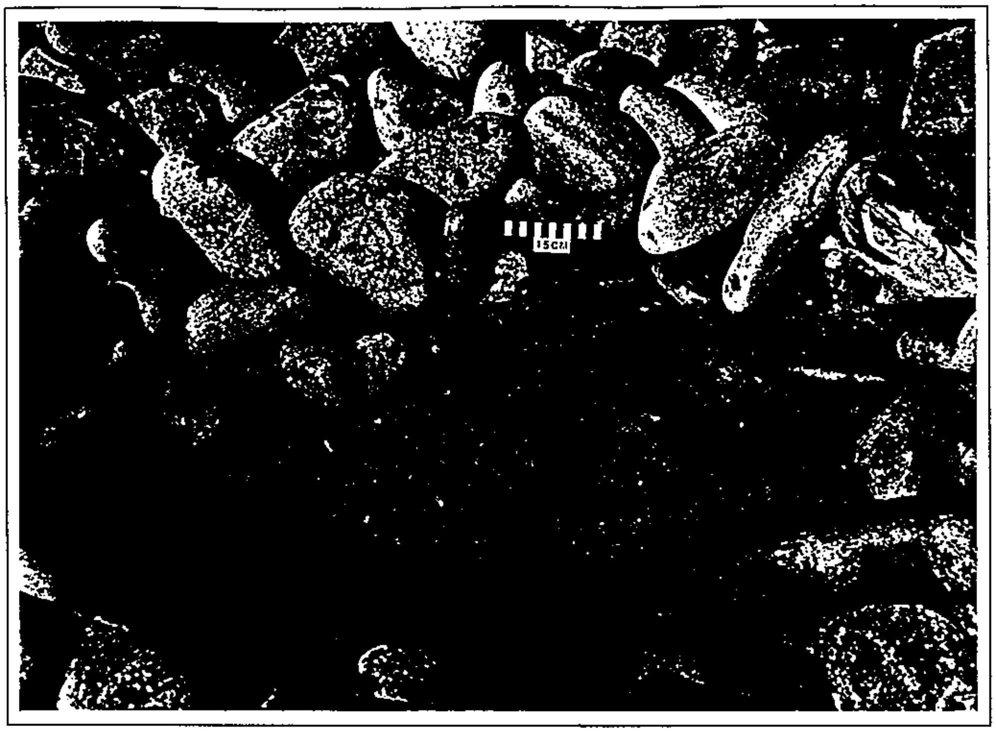

100
90
80
70
60
50
40
30
20
10
0
Percent
N-15 28 Aug 91
Latouche Island
0
10
20
30
40
50
60
70
80
90
Meters
Boulder
Cobble
Pebble

Figure 22. (Facing Page) Photographs of trenches dug on the upper platform of station N-15.

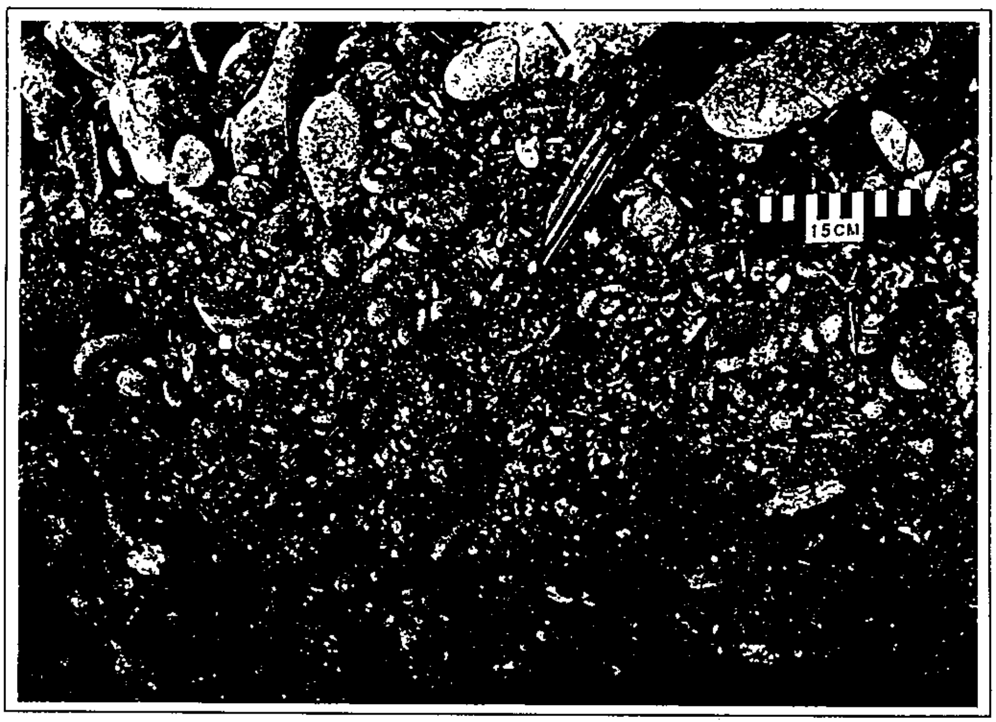
A. Trench dug in the middle of the upper platform on May 26, 1990. The surface cobbles were relatively clean on this date, whereas heavy oil remained at depth under the cobble armor. Photo by M. Hayes.

B. Trench dug in the upper part of the upper platform on August 28, 1991. The armor had been disrupted by the berm-relocation process, and the subsurface oil was greatly reduced. Compare with trench description (A) in Figure 23. Photo by J. Michel.

A.



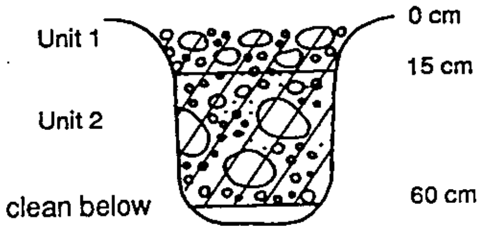
B.

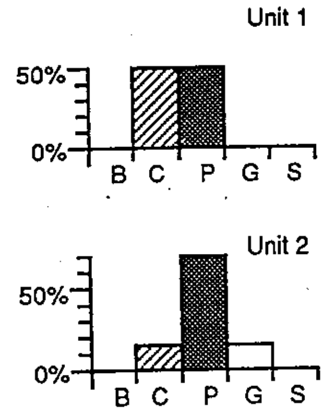


N-15 LATOUCHE ISLAND, 28 August 1991

▨ - Oiled Zone

TRENCH A

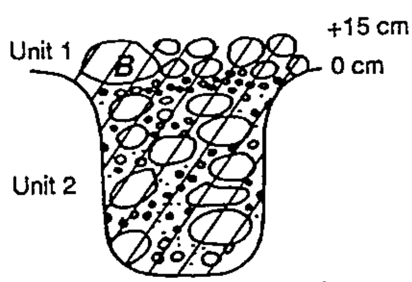


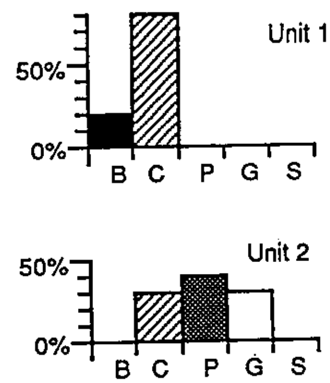


Unit 1: Reworked surface layer with 5% stain.

Unit 2: All clasts have greasy oil coating to 60 cm. Sampled 25-50cm (1B). Below is clean zone of iron-stained clay/pebbles.

TRENCH B





Unit 1: Cobble armor with 50% stain, overlying pebble zone.

Unit 2: Mixed cobble, pebble, granule zone. Well rounded. Lightly oiled from 0-35cm, sampled from 20-30cm (2B). Moderately oiled from 40-50cm, sampled (3B).

Figure 23. Description of two trenches dug at station N-15 on August 28, 1991. Note disruption of armor in trench A and the beginning of recovery of the armor at trench B. Subsurface oil was greatly reduced in both trenches, presumably as a result of the berm-relocation process.

Station 17 (Perry Island)

This station has been surveyed only seven times, primarily because the area was closed during the eagle-nesting season in 1990. It was also the site of a berm-relocation project in late August 1990. The station was resurveyed during both of the 1991 surveys (January 20 and August 29).

This beach is subject to considerable wave action because it is located on a small east-facing pocket beach near the south end of Perry Island. It has an erosional/ depositional cycle that was clearly discernible from the earlier beach surveys (Michel and Hayes, 1991); therefore, by the time of the January 20, 1991, survey, the sediments disrupted by the berm-relocation process had been completely returned to their normal configuration along the beach profile. The beach is backed by a fresh-water lagoon that generates a strong flow of groundwater through the coarse and well-sorted sediments. The combination of: (a) the relatively large (for PWS) wave-energy flux; (b) the intense groundwater flushing; and (c) the berm-relocation project produced an essentially clean beach by the time of our survey in August 1991. Even the patches of asphalt pavement behind the large rock outcrop in the middle of the beach had been removed.

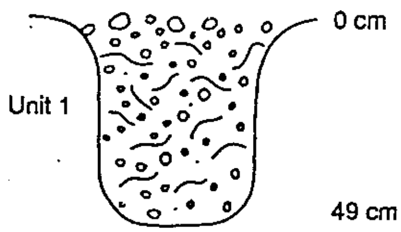
Three trenches were dug along the profile during the August 29, 1991, survey (Figure 24). No oil was found in trenches A and C, but a possible oil film occurred at depths of 15 to 35 cm in trench C. A sample of this sediment is being analyzed to determine its composition and source.

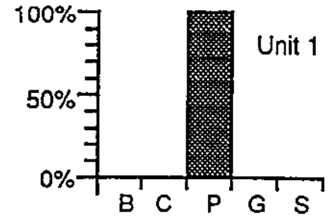
In summary, this is the first of the cobble-boulder platforms with berms stations that we studied to be essentially cleaned of all surface and subsurface oil since the spill.

N-17 PERRY ISLAND, 29 August 1991

- Oiled Zone

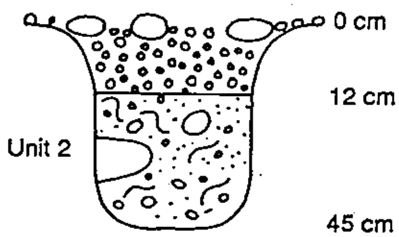
TRENCH A

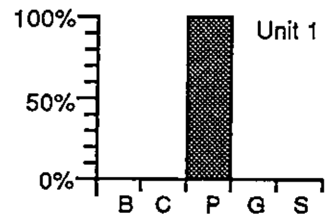




Unit 1: Rounded pebbles, large amount of degraded detrital material. No oil.

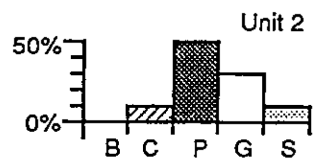
TRENCH B



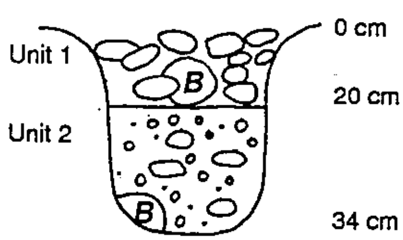


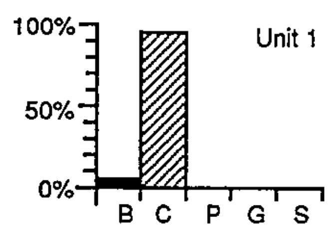
Unit 1: Pebble zone below surface layer with 20% cobbles, no oil.

Unit 2: Poorly sorted zone, with larger amounts of degraded detrital material. High ground water flow rate. Water table at 30cm depth. Sampled 20-30cm (1B). No visible oil.



TRENCH C





Unit 1: Surface layer of clean cobbles.

Unit 2: Mostly pebbles; few small sheens on water table - may be organic.

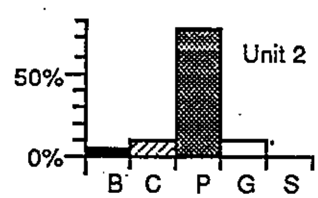


Figure 24. Description of the trenches at N-17 on August 29, 1991. Note the near absence of any subsurface oil. Trenches A and B were located in the zone of active high-tide berms and trench C was located on the steep cobble/boulder platform, which has excellent armoring.

Beaches with Mobile Fine Gravel

Introduction

Two of the NOAA stations, N-4 on Smith Island and N-18 in Sleepy Bay, reacted somewhat differently than the other gravel beaches studied with respect to both subsurface oil behavior and response to berm-relocation projects. Both of these stations have an abundance of finer gravel sediments in the middle to upper intertidal zone; mostly pebbles and granules, with some cobbles, that are relatively mobile. Consequently, they showed frequent shifts in both sediment distribution patterns and beach morphology over time.

Station N-4 (Smith Island)

This beach, located on the northeast end of Smith Island and exposed to a long fetch in a northeasterly direction (40 to 45 km), is classified in the category cobble-boulder platforms with berms. However, several characteristics distinguish it from the other beaches in its class:

1) The sediment veneer is very thin over the raised rock platform, and several rock outcrops are present.

2) There is an abrupt change in sediment size at about mean sea level, with finer gravel dominating the upper half of the intertidal zone and a heavy boulder armor the lower half.

3) The sediment on the upper half of the beach is highly mobile, with several cycles of construction and then erosion of spring and neap berms having occurred during the study period.

4) There is no major storm berm and the beach is backed by a raised vertical scarp (see field sketch in Figure 25). These features indicate that coarse gravel sediments are scarce, the wave energy flux is exceptionally high, or a combination of the two occurs at this site.

In summary, this beach is principally an uplifted rocky shore platform with highly mobile fine gravel berms at the high-tide line, and a stable armor of cobbles and boulders on the lower half of the intertidal zone.

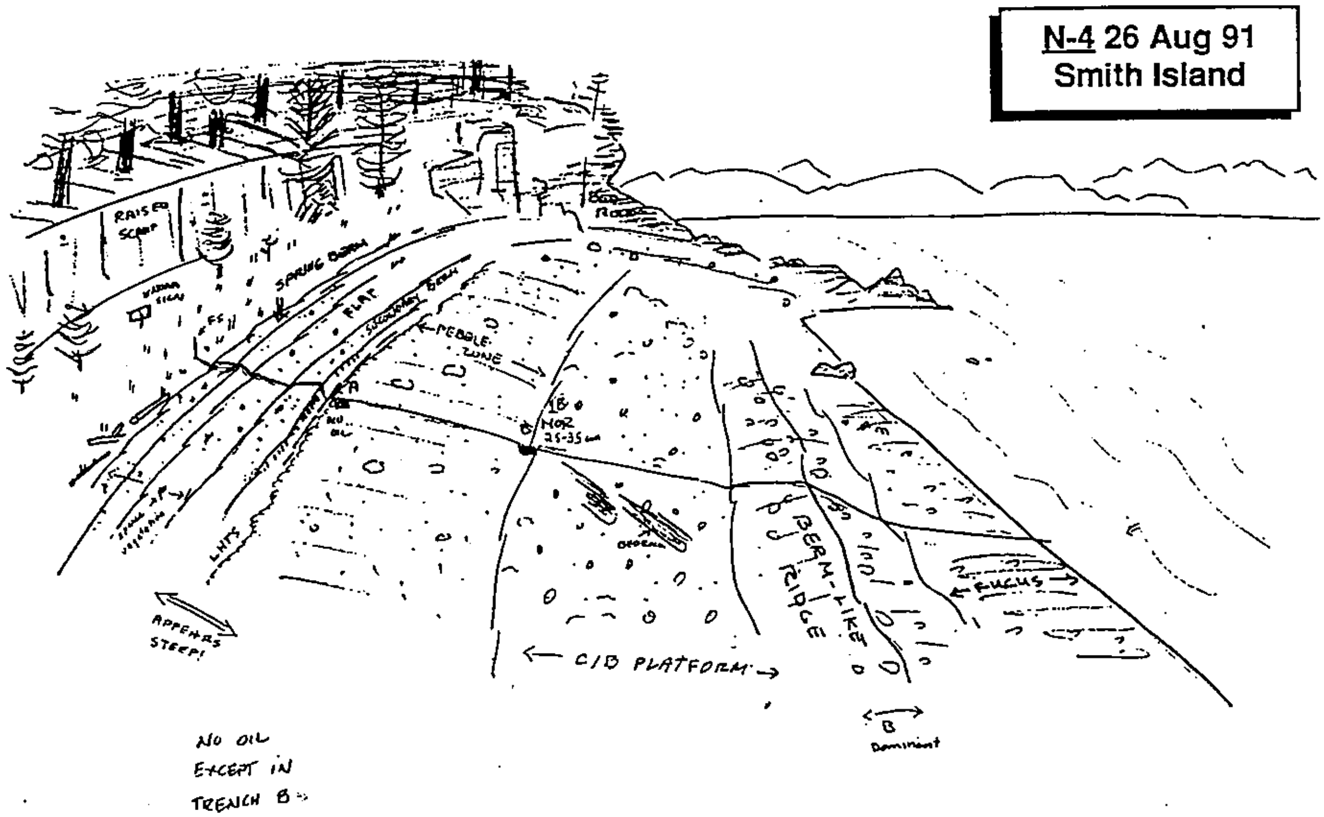


Figure 25. Field sketch of station N-4, on the northeast end of Smith Island, on August26, 1991. Note the clear difference between the lower and upper half of the intertidal zone, the upper part being either smoothed out pebbles or minor pebbly berms and the lower half being a heavily armored cobble-boulder platform.

As stated above, this station is prone to undergo relatively rapid minor changes, particularly in the high-tide berm area. Therefore, the fact that the beach recovered rapidly after a berm-relocation project in August 1990 was no surprise. As shown by the beach profile plot in Figure 26A, this berm-relocation project was entirely within the upper intertidal zone, which aided the rapid recovery. By January 21, 1991, the excavated pit at the high-tide line had been completely refilled by wave action. However, about half of the excavated sediment was apparently transported longshore. Our observations in January 1991 indicated that this sediment was transported to the western side of the pocket beach where it was deposited into a high cuspate berm. The surface grain-size distribution plots given in Figure 27 illustrate how highly mobile the sediments of the high-tide berms area are at this station. This beach was an ideal site for a berm-relocation project because of the exceptional mobility of the sediments. The survey of August 26, 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 (Figure 26C).

Data on the subsurface oil at this site, given in Figures 28 and 29, indicate that the berm relocation at station N-4 successfully aided the cleanup of the high-tide berm portion of the beach. Both the trench description (Figure 28) and the TPH data (Figure 29) show that the subsurface oil that had persisted in that part of the beach until August 1990 was no longer there when the August 1991 survey was carried out. In the part of the profile not impacted by the berm-relocation project (the zone below the high-tide berms) some subsurface oil was still present in the form of a moderate oil residue. This subsurface oil must have a patchy distribution, however, because it was not found in the trenches dug during the summer 1990 and January 1991 surveys.

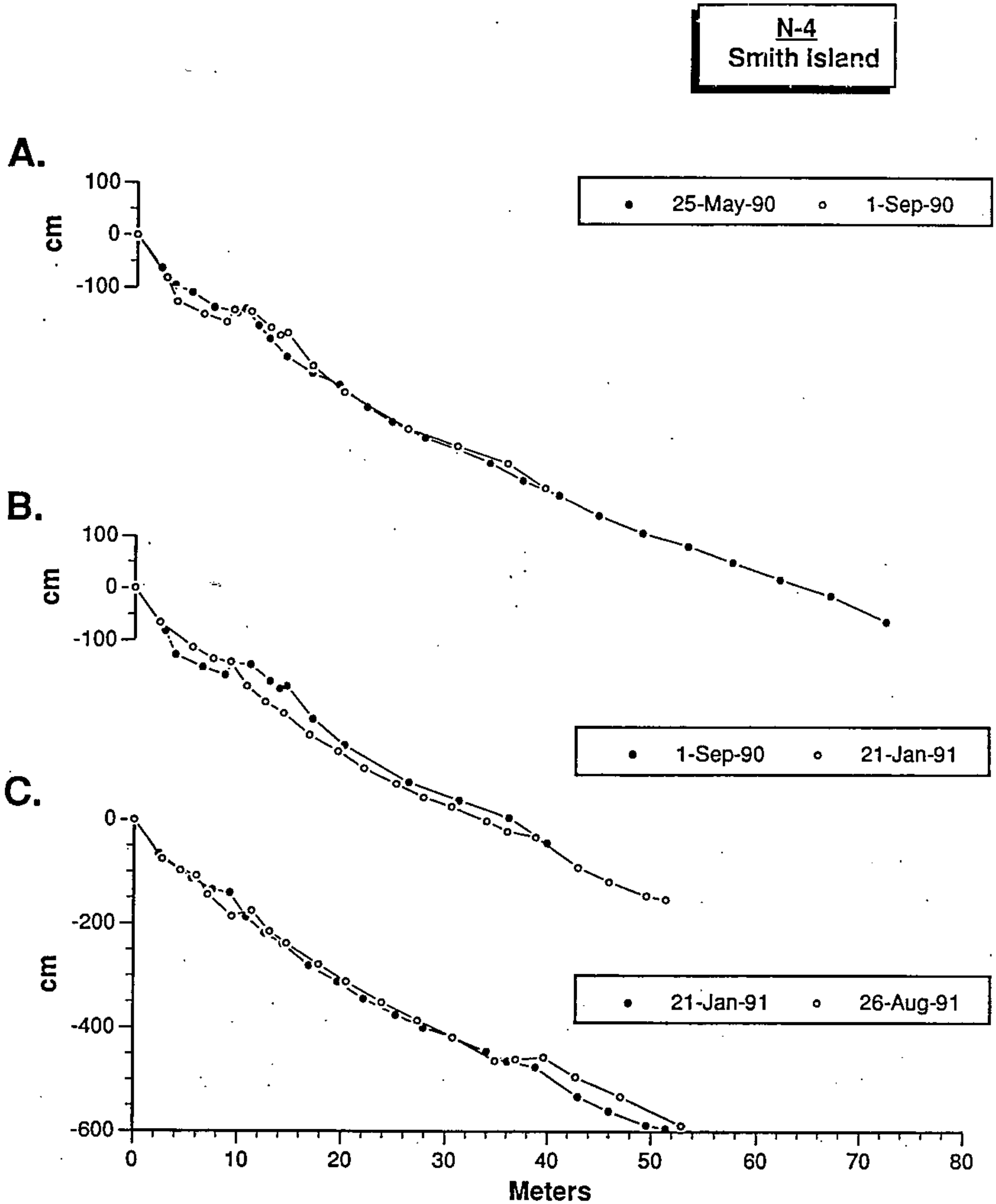
Though located a short distance from station N-3 and having a very similar hydrodynamic setting, as well as having been subjected to a similar berm-relocation project, the beach at N-4 simply does not show the same tendency to retain subsurface oil. The probable causes of these differences are a somewhat steeper slope and a thinner veneer of surface sediments. The sediments are thicker and coarser at station N-3 and most of the sediments of the upper intertidal zone of station N-4 are probably entirely remobilized during storms. These factors also aid hydraulic flushing at this station relative to station N-3.

Figure 26. (Facing Page) Temporal changes in the beach profile at station N-4.

A. Comparison of May 25, 1990, and September 1, 1990, profiles. Note the excavation pit left as a result of a berm-relocation project carried out in August 1990. The excavated sediment was piled a small distance seaward of the pit. By the September survey, part of the excavated sediment had been reworked by waves into a smooth-faced berm.

B. Comparison of September 1, 1990, and January 21, 1991, profiles. The excavation pit had been filled in by wave action by the January survey; however, the sediment pile seaward of the pit was entirely removed and part of the sediment had been transported along the beach to the west.

C. Comparison of January 21, 1991, and August 26, 1991. Profiles that show little perceptible change, except for the buildup of a large berm-like ridge on the lower platform.


N-4
Smith Island
A.
100
0
-100
cm
25-May-90
1-Sep-90
B.
100
0
-100
cm
1-Sep-90
21-Jan-91
C.
0
-200
-400
-600
cm
21-Jan-91
26-Aug-91
0
10
20
30
40
50
60
70
80
Meters

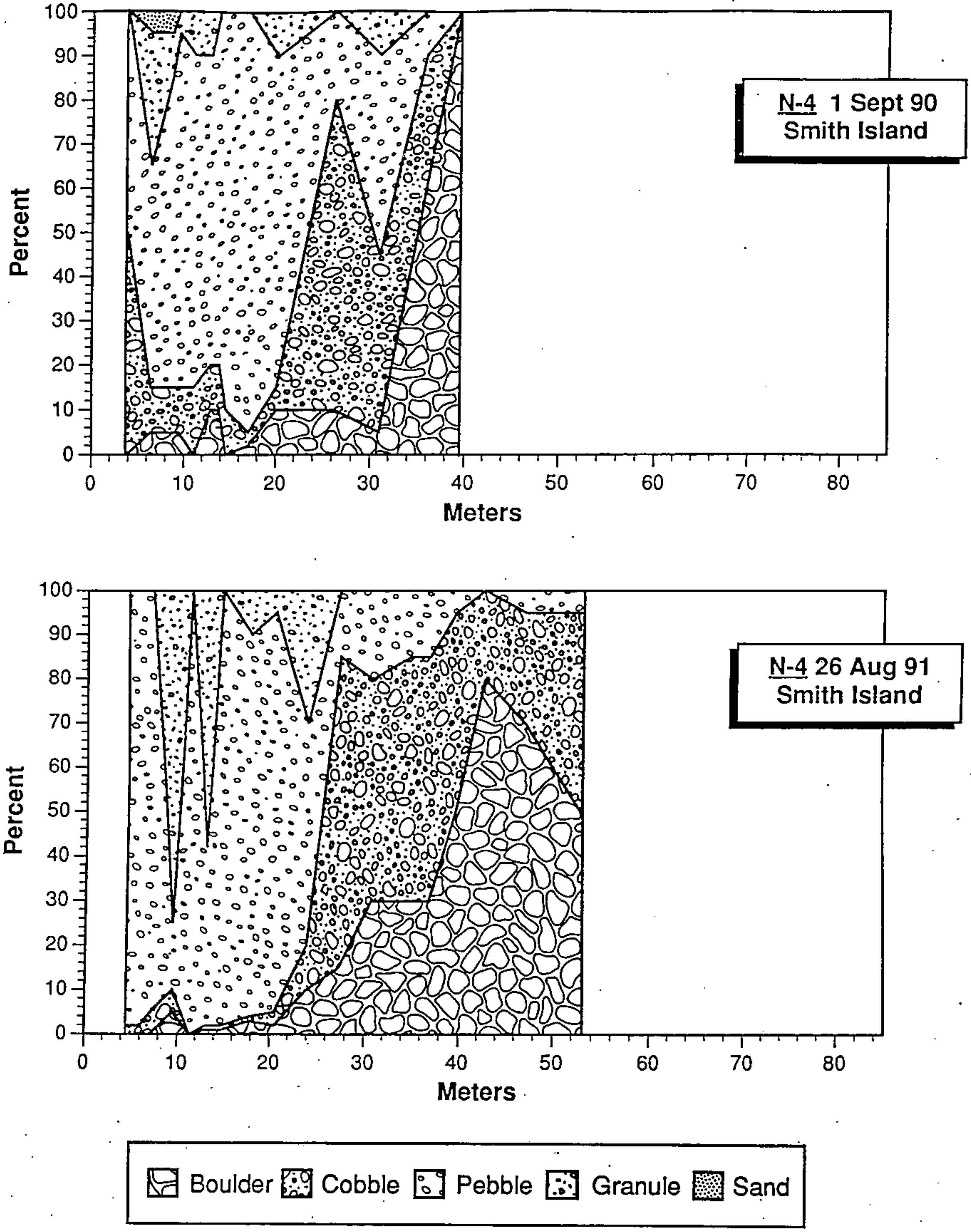
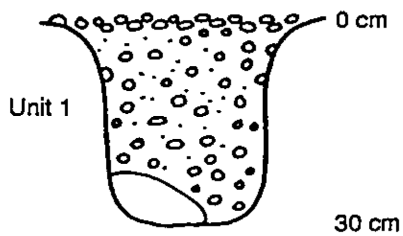


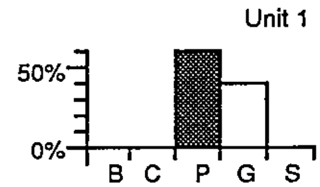
Figure 27. Surface grain-size patterns along station N-4 on September 1, 1990, and August 26, 1991, showing the change resulting from wave reworking of the sediments disturbed by the berm-relocation project of August 1990.

N-4 SMITH ISLAND, 26 August 1991

- Oiled Zone

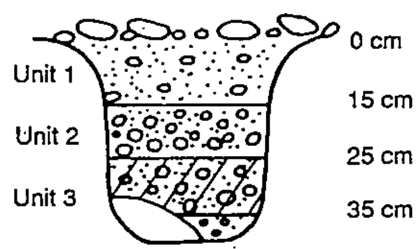
TRENCH A

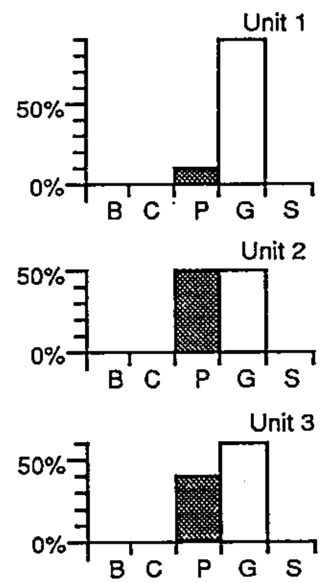




Unit 1: Uniform mix of pebbles and granules. No oil.

TRENCH B





Unit 1: No oil.
Unit 2: No oil.
Unit 3: Moderate oil (MOR). Small brown sheen on water table. Clean below. Sampled 25-35cm, whole oiled zone.

Figure 28. Trenches dug at station N-4 on August 26, 1991. Note the lack of surface armoring at these two sites. Moderate oil residue was present at 25 to 35 cm in trench B, located on the upper platform (Figure 25A). This was the first subsurface oil observed at this site in a year.

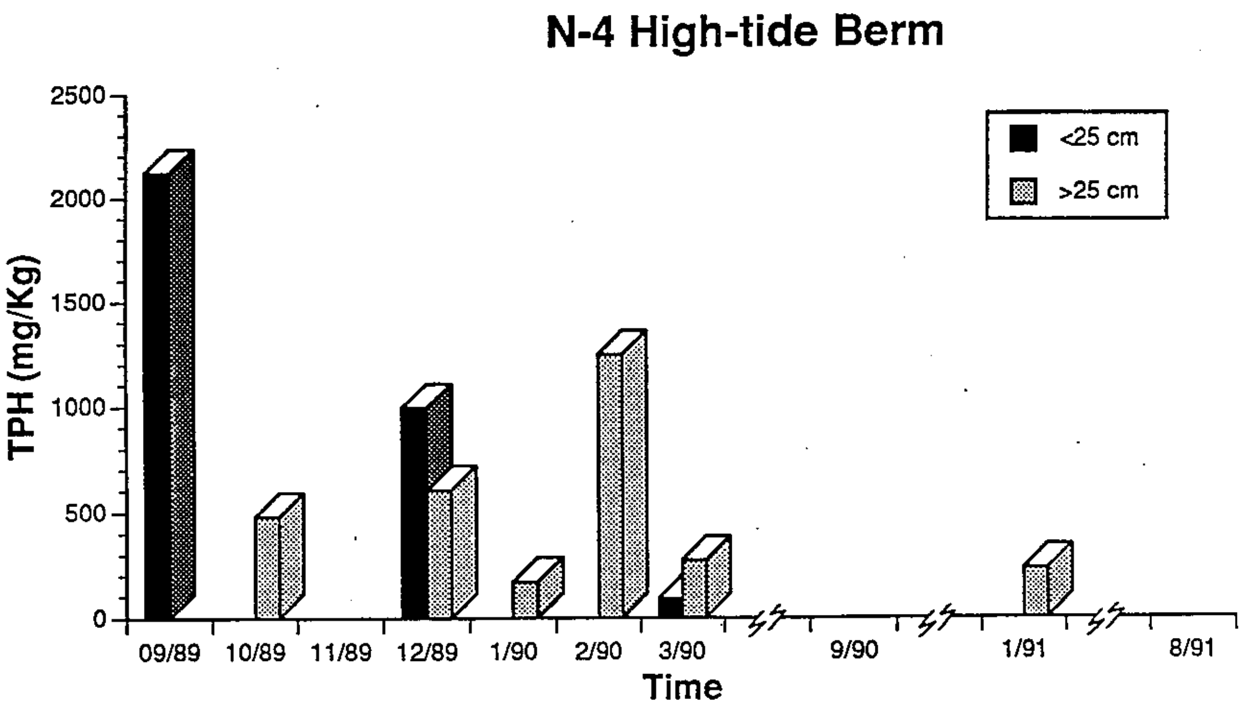


Figure 29. TPH data for the high-tide berm area at station N-4. All subsurface oil had been removed from this area by the August 26, 1991, survey.

Station N-18 (Sleepy Bay)

This station is located at the south end of Sleepy Bay; a north-south oriented indention of the north end of Latouche Island. It is somewhat unique for our stations in that it is bisected by a small anadromous stream that is host to a run of pink salmon each August. This stream, which has built a small delta, constantly shifts position, creating significant changes in the profile. The beach is somewhat sheltered; but, judging by the way it has changed over time it is the site of periodically significant wave action, presumably as a result of its northerly orientation and a northeasterly fetch of 25 km from the entrance to the bay.

The intertidal zone at this station, surveyed ten times during the study, consists of three morphological subdivisions (Figure 30, lower): (1) high-tide berms, which are constantly changing; (2) stable central ramp, an extremely stable area; and (3) low-tide bars, a zone of bar growth and migration caused by changes at the stream mouth. The magnitude of the changes that can occur at this station is illustrated by the profile plots in Figure 30, lower, compare the profiles measured on September 5, 1990, and January 22, 1991. During that interval, the high-tide berms were eroded off flat, the whole central portion of the profile was lowered 10 to 20 cm (on the average), and a major bar was built across the lower intertidal zone (as illustrated in field sketch in Figure 30, upper). The stream channel had migrated approximately 50 m to the east since the previous September, crossing the profile line for the first time during the study. This primarily erosional episode had exposed previously buried oil all along the upper one-third of the profile.

The head of Sleepy Bay was an area of special concern because of the presence of the anadromous stream and the persistence of the subsurface oil. A wide range of treatment techniques were tried, but significant subsurface oil remained as late as the January 22, 1991, survey (Michel and Hayes, 1991). All five of the trenches dug on that date contained moderate to heavy amounts of subsurface oil. A sample collected from a depth of 30 cm in trench B (Figure 30B) contained 34,900 mg/kg oil; the highest value ever measured at this station.

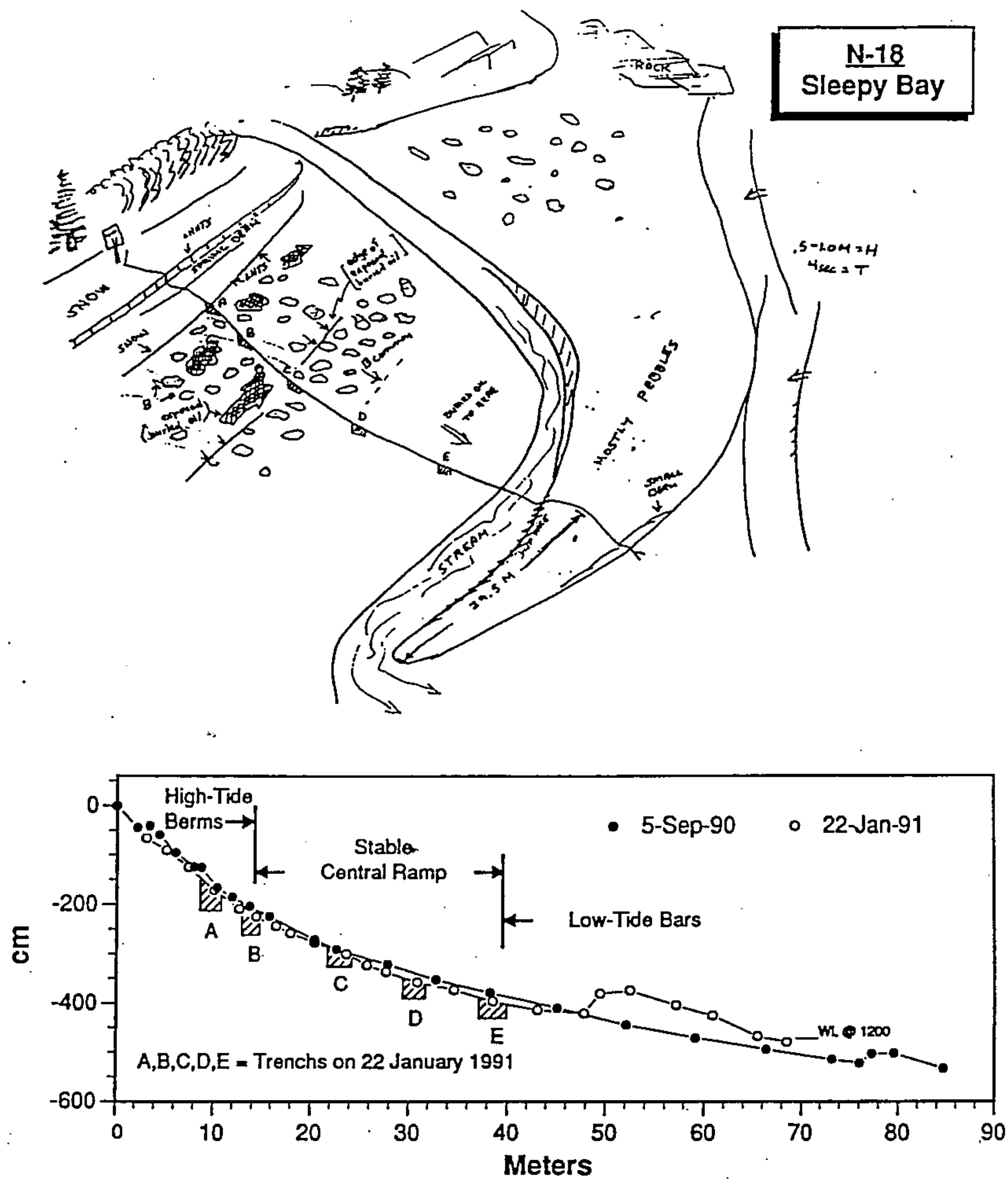


Figure 30. Station N-18, located at the head of Sleepy Bay. (Upper) Field sketch on January 22, 1991. The stream had migrated to the east across the profile since the site was visited on September 5, 1990. Erosion had exposed patches of oil in the upper intertidal zone that had previously been restricted to the subsurface. (Lower) Comparison of the September 5, 1990, and January 22, 1991, profiles. The high-tide berms and the stable central ramp area were eroded during this interval, and a large intertidal bar had formed in the lower intertidal zone.

The beach at the head of Sleepy Bay was subjected to extensive mechanical removal of the oiled sediments in the summer of 1991 eliminated much of the remaining subsurface oil. The field sketch in Figure 31A shows that the disturbance of the profile resulting from the cleanup process at station N-18, was still evident as of August 28, 1991. The beach profile (plotted in Figure 31B) showed that a modified swash bar had developed around a mass of coarse material that had been piled on top of the central ramp during the cleanup process. Two of the trenches dug on August 28, 1991, are compared with trenches dug on 24 May 1990 in Figure 32. Most of the subsurface oil had been removed from the site by August 1991, but some remained in the form of light to moderate oil residues. The TPH plots in Figure 33 show that only a trace of subsurface oil remained in the central ramp; an area noted for very high readings for most of the earlier surveys. Thus, the physical reworking of the heavily oiled mid-tidal zone just east of the stream appeared to be successful. It is expected that the beach profile at Sleepy Bay will rapidly return to normal during the storm season, as it has done following physical disturbance every year since 1989.

N-18
Sleepy Bay

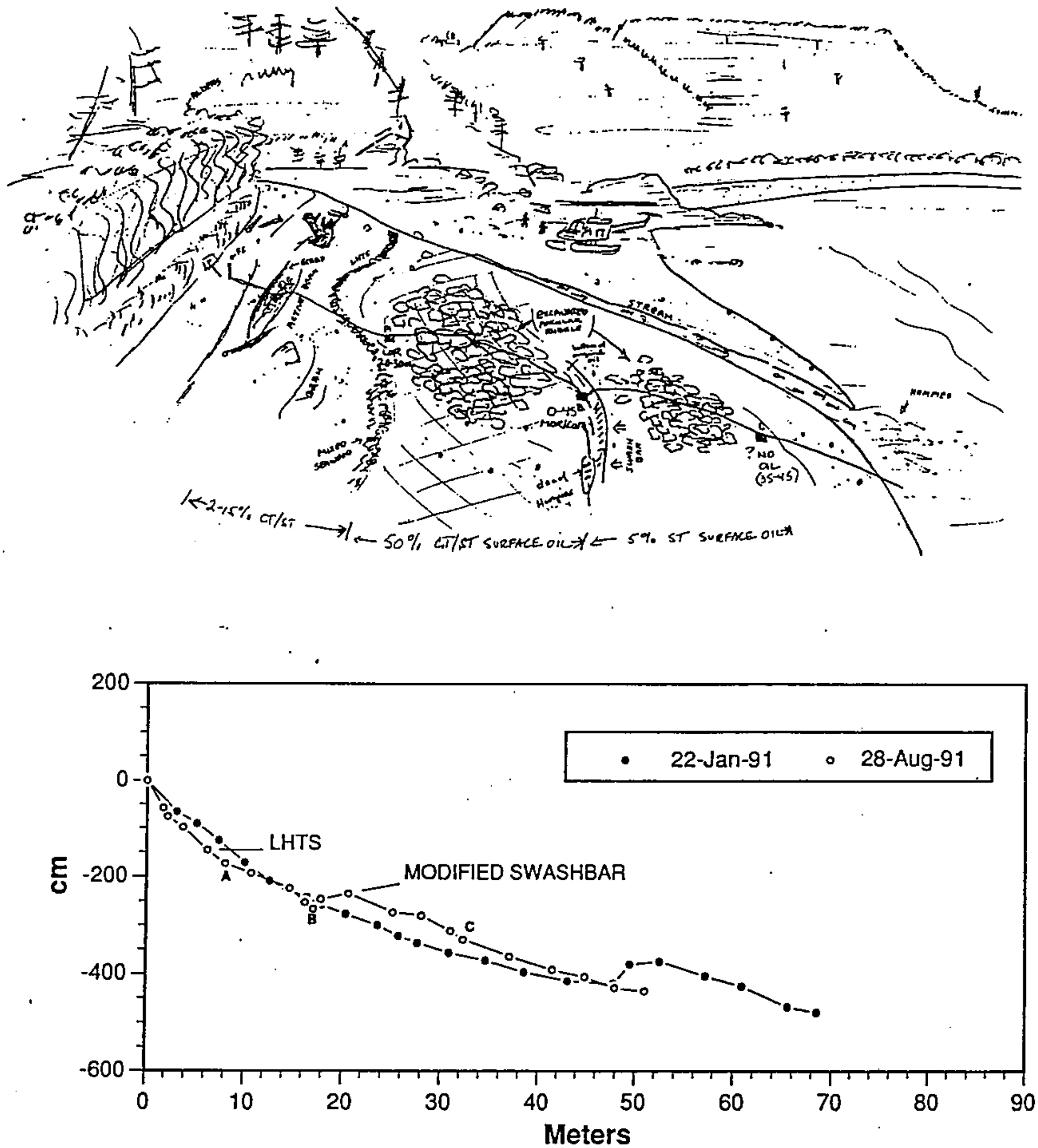


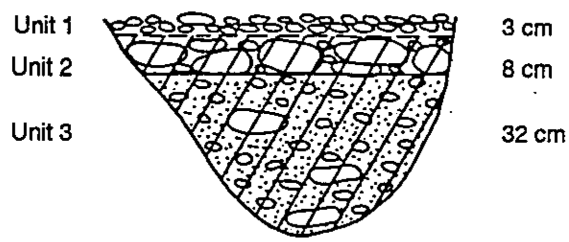
Figure 31. (Upper) Station N-18, Sleepy Bay. Field sketch on August 28, 1991, showing evidence of the cleanup process carried out earlier in the summer. Much of the subsurface oil had been removed.

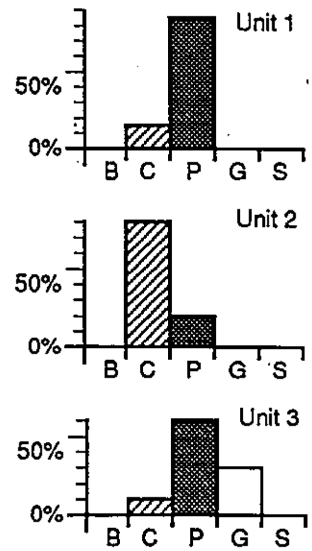
(Lower) Comparison of the August 28, 1991, and January 22, 1991, profiles. A modified swash bar had developed on top of the disturbed coarse-grained sediments on the central ramp.

N-18 SLEEPY BAY, 24 MAY 1990

- Oiled Zone

TRENCH A

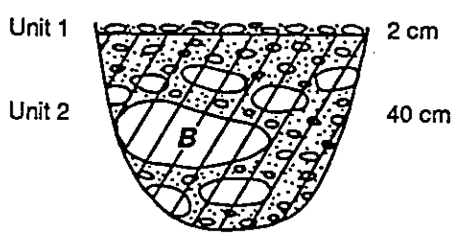


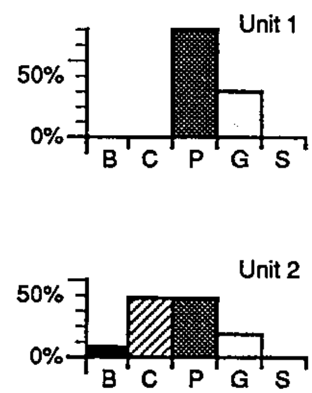


Unit 2: Heavy mousse coating, medium brown
Oiled layer of spruce needles at top

Unit 3: Light mousse coating, medium brown
Scattered wood and spruce needles

TRENCH B





Unit 2: Mousse coating, medium brown
Pores not filled
Scattered spruce needles

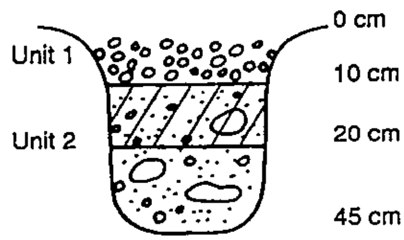
Figure 32A. Trench descriptions at station N-18 (Sleepy Bay).

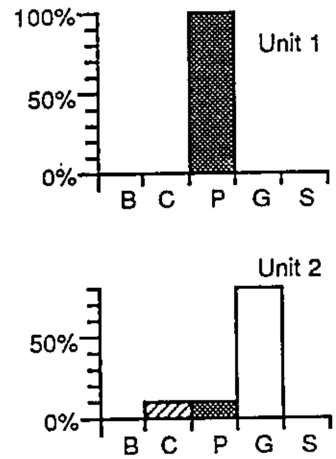
Trenches dug on May 24, 1990. Note absence of armoring and abundance of subsurface oil.

N-18 SLEEPY BAY, 28 August 1991

- Oiled Zone

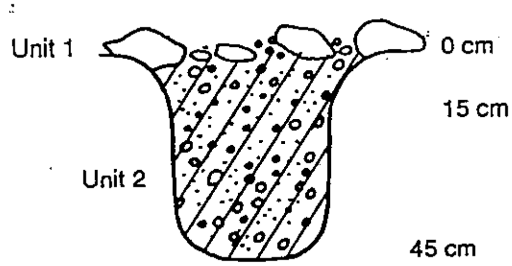
TRENCH A

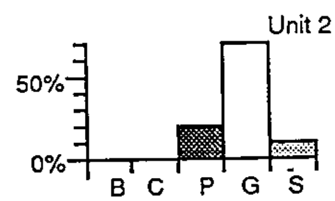




Unit 1: Clean pebble zone.
Unit 2: Lightly oiled at 10-20cm depth. Clean below.

TRENCH B

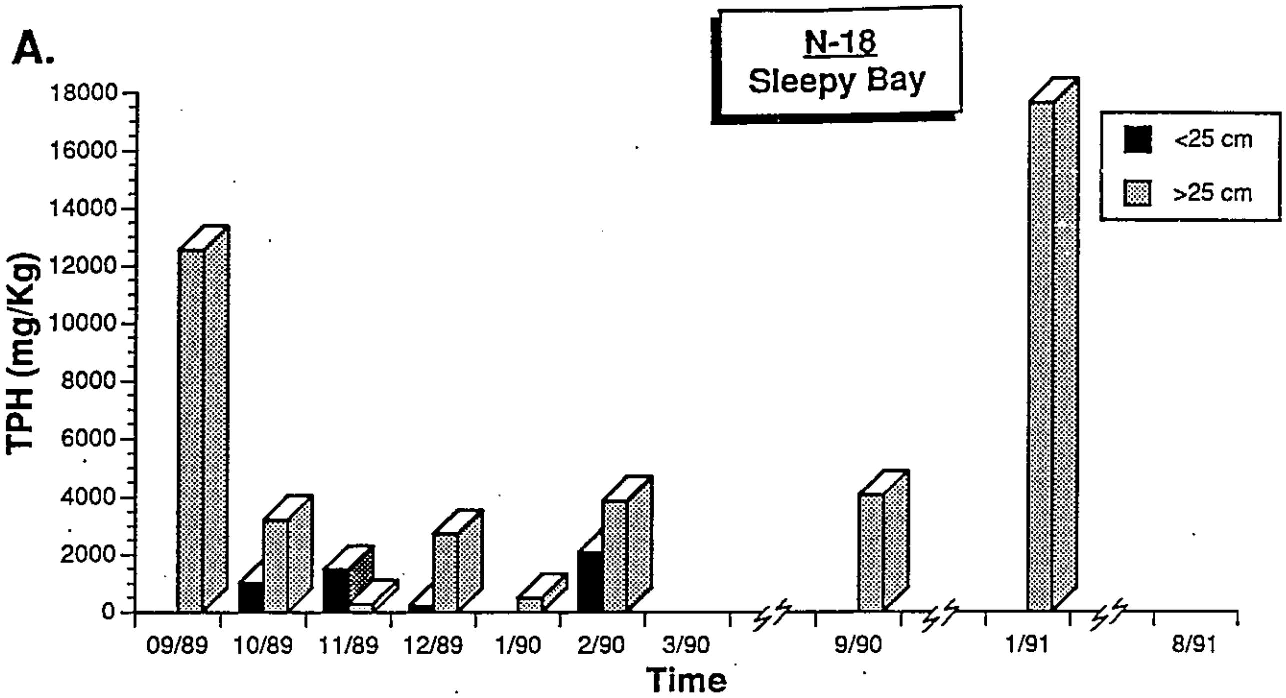




Unit 1: Irregular surface rubble, angular.
Unit 2: Mostly granules; moderately oiled (MOR) 0-15cm and sampled (2B); lightly oiled 15-45cm and sampled (1B).

Figure 32B. Trenches dug on August 28, 1991. Note the relative paucity of subsurface oil compared to the earlier surveys.

A.



B.

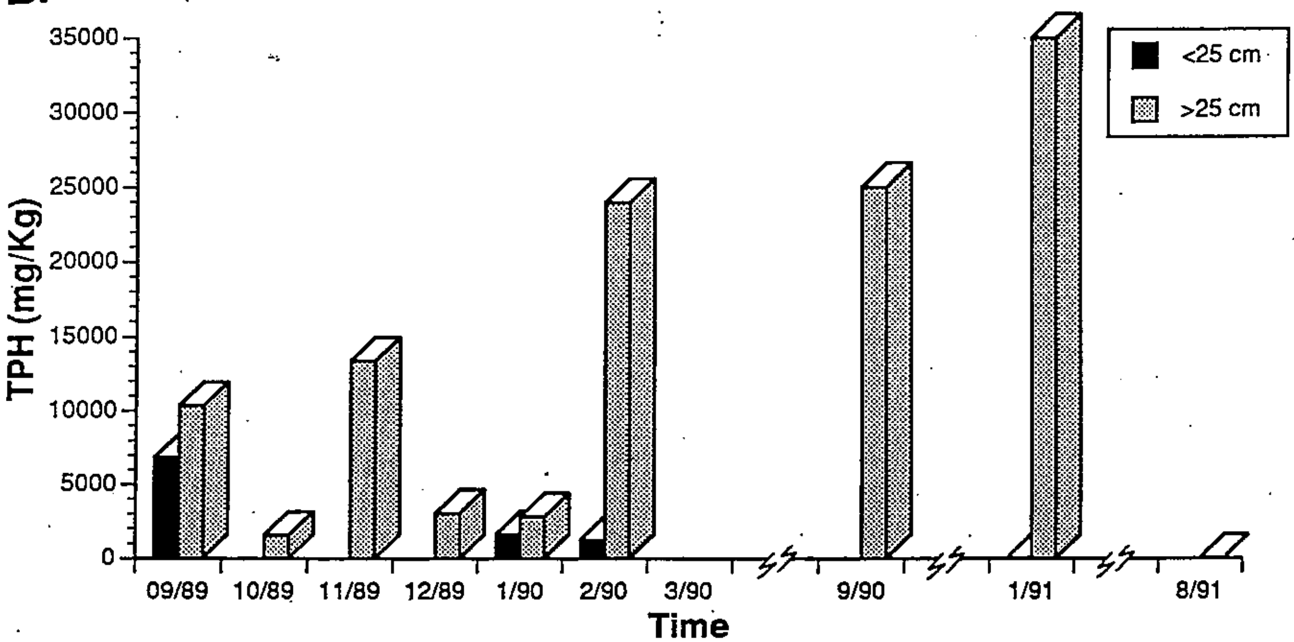


Figure 33. TPH data for station N-18, Sleepy Bay.

A. Data for the high-tide berm area. After the February 1990 survey, the top 25 cm of sediment were clean, whereas deeper subsurface oil remained. Data for the August 1991 samples are not yet available.

B. Data for the central ramp area. This area had always had significant subsurface oil until it was removed manually in the summer of 1991.

Stations in Sheltered Locations

Introduction

During the August 1991 survey, six of the permanent stations located in sheltered areas were visited. They were stations N-11 and N-12 on Crafton Island, stations N-10 and N-13 in Herring Bay, station N-5 in Snug Harbor, and station N-6 in the Bay of Isles (Figure 1). All of these stations have retained at least small amounts of oil throughout the study period, usually in the subsurface sediments. Each station presents a slightly different mode of oil retention, usually depending on sediment type, cleanup history, geomorphic origin, and possibly, other factors.

Stations N-11 and N-12 (Crafton Island)

These two stations, which are illustrated by the field sketch in Figure 34, are located near the middle of the west side of Crafton Island on the inside of a small, circular indention in the shoreline. Because of its position inside the small embayment, which has a large rock blocking its entrance, the shoreline is quite sheltered from wave action. With respect to their classification, the two stations are basically hybrids, falling between what was called pebble beaches with tidal flats and rocky rubble slopes with raised bay bottoms in our earlier report (Michel and Hayes, 1991). This is a sensitive ecological area because of the presence of a well-developed eelgrass bed just beyond the mean-low-water mark. The sediments are impermeable or remain water-saturated at low tide; thus, subsurface oil has been restricted to very shallow depths. Cleanup of this site has been mostly by manual removal of the fairly extensive thin asphalt pavements, especially near profile N-12 (Figure 34) and through applications of Inipol™ and Customblen™ fertilizer.

When we surveyed the two stations on August 29, 1991, they were by far the most free of oil we had seen them. However, as shown by the sketch in Figure 34, there were still some random thin and weathered patches of asphalt pavement present. Many of the surface oil residues showed evidence of manual removal, and Customblen shells were abundant.

The two trenches dug at station N-11 are illustrated in Figure 35. There were some traces of residual oil in an organic-rich zone of shallow (5 to 10 cm) subsurface sediments near the high-tide line. Detailed chemical analyses will be necessary to differentiate between natural organics and residues from the *Exxon Valdez* oil in these subsurface sediments.

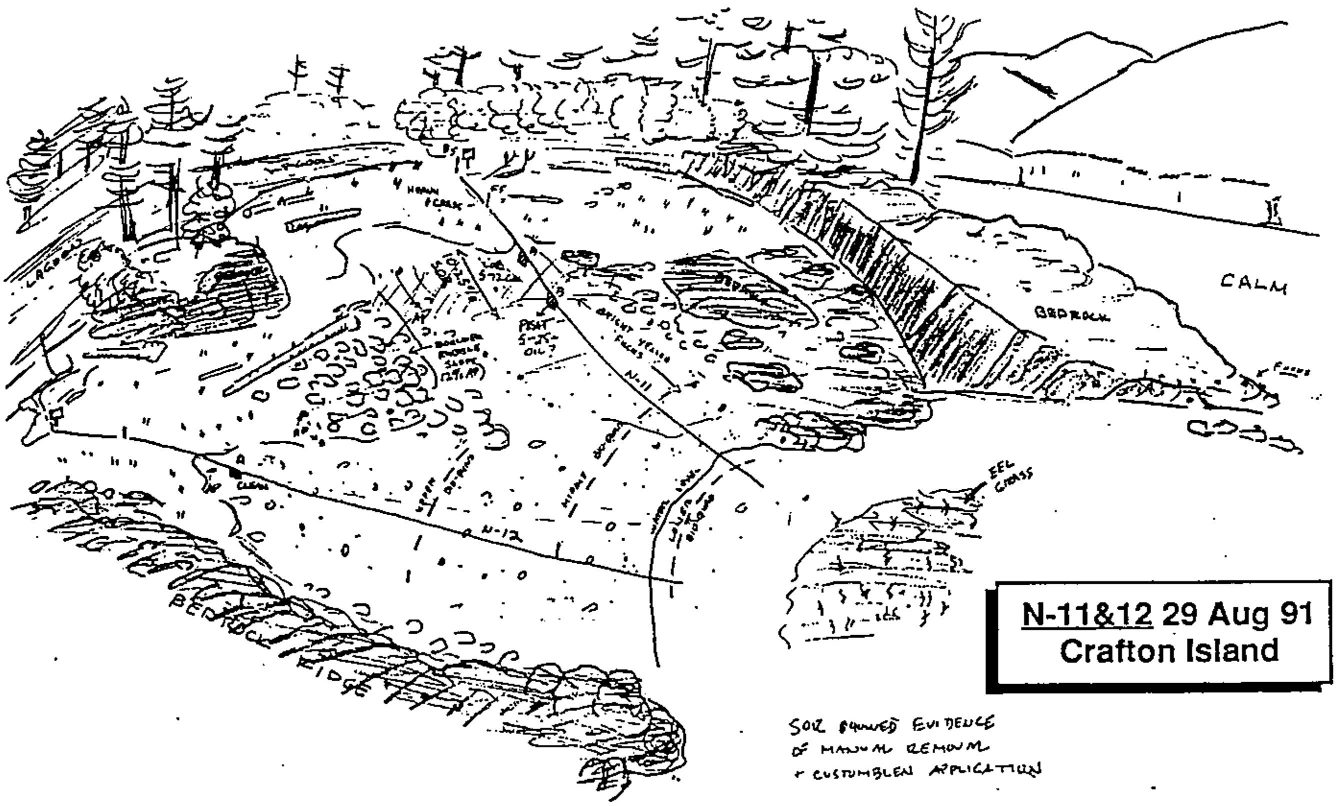
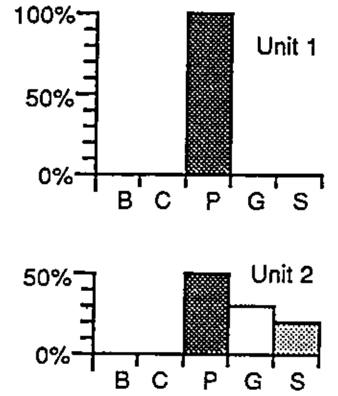


Figure 34. Field sketch of stations N-11 and N-12 on August 29, 1991. Note random distribution of small patches of asphalt pavement near the high-tide line, as well as the shallow submerged eelgrass bed.

N-11 CRAFTON ISLAND, 29 August 1991

- Oiled Zone

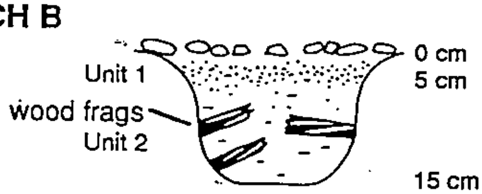
TRENCH A

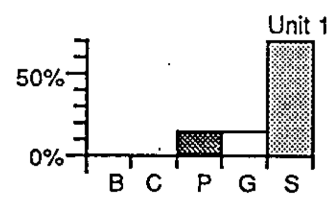


Unit 1: Surface layer of angular pebbles. Sampled 0-5cm (2B). No oil. Oxidized zone.

Unit 2: Organic-rich zone, with oily film. Mostly angular pebbles. Sampled 5-12cm (1B), which is the oily zone. Formed sheens on high water table.

TRENCH B





Unit 1: Surface veneer of angular pebbles (no oil) overlying sandy zone. Slight sheen on high water table.

Unit 2: Organic rich silt with abundant wood fragments.

Figure 35. Description of trenches dug at station N-11 on August 29, 1991.

Sheltered Rocky Coasts [Station N-10 (Herring Bay) and Station N-6 (Bay of Isles)]

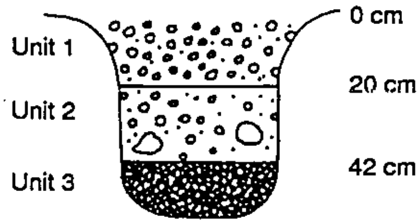
Of these two stations, N-10 is by far the most exposed, being located on the east side of the entrance to Herring Bay, Knight Island (Figure 1). The profile is positioned over a cluster of rock outcrops that provide their own sheltering effect for the landward portion of the complex. Until the August 27, 1991, survey, a heavily oiled tombolo composed of pebbles was located at the high-tide line on the profile in the lee of the major rock outcrop. As shown by the trench description in Figure 36 (trench A), however, this area was free of oil as of the August 27 survey due to manual removal during the summer of 1991. Trench B (Figure 36), which was located about 11 m seaward of the high-tide line, contained an asphalt pavement underneath some surficial boulders that had a 10 percent cover of coat and stain, mostly on the undersides and vertical faces of the boulders. The surfaces of the boulders and bedrock were free of oil, except in deep crevices.

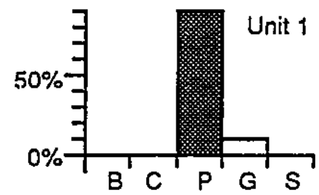
A well-developed pebble beach with multiple high-tide berms is located just to the north of station N-10. In May 1990, our team discovered a 14-cm-thick layer of subsurface oil at 62 cm below the surface of the lower beachface. Although this site was the subject of a berm-relocation project in the summer of 1990, the same layer was present when we surveyed the site on August 27, 1991. A description of the trench dug on that date, which was located 55 m north of the N-10 profile line, is given in Figure 36 (trench C).

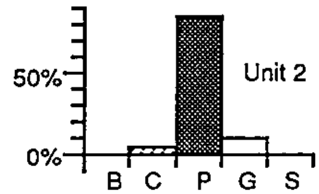
N-10 HERRING BAY, 27 August 1991

- Oiled Zone

TRENCH A

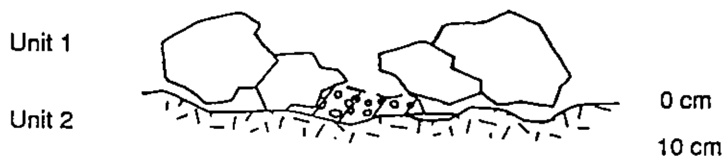






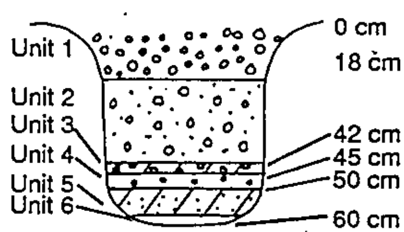
Unit 1: No visible oil on rounded pebbles.
Unit 2: No visible oil. Film of organics/muddy fines. Sampled 35-38cm (1B).
Unit 3: Peaty organics.

TRENCH B



Unit 1: Surface boulders; 10% coat/ stain.
Unit 2: 100% pebbles, oil-cemented between boulders and overlying bedrock. Strong sulfur odor. Sampled 5-10cm (2B). Customblen shells on surface.

TRENCH C



Unit 1: 100% small pebbles.
Unit 2: Banded layer of pebbles and granules.
Unit 3: Layer of oiled pebbles.
Unit 4: Clean layer of pebbles and granules.
Unit 5: 10 cm layer of oiled pebbles/ granules; fresh, greasy oil.

Figure 36. Description of trenches dug at station N-10 on August 27, 1991. Trench A was located at the high-tide line on the profile, the former site of a heavily oiled pebble tombolo. Trench B was located 11 m seaward of trench A (on the profile line). Trench C was located 55 m north of the profile line, within the lower intertidal zone of the adjacent pebble beach.

Station N-6 is located on a steep, south-facing protuberance of bedrock (Figure 37) near the head of the west arm of the Bay of Isles on Knight Island. It is a very sheltered location with respect to wave action. The surficial sediment on the bedrock is there as a result of normal weathering processes. This station was a set-aside and it has provided many insights into the process of natural weathering of oil on a sheltered bedrock shore.

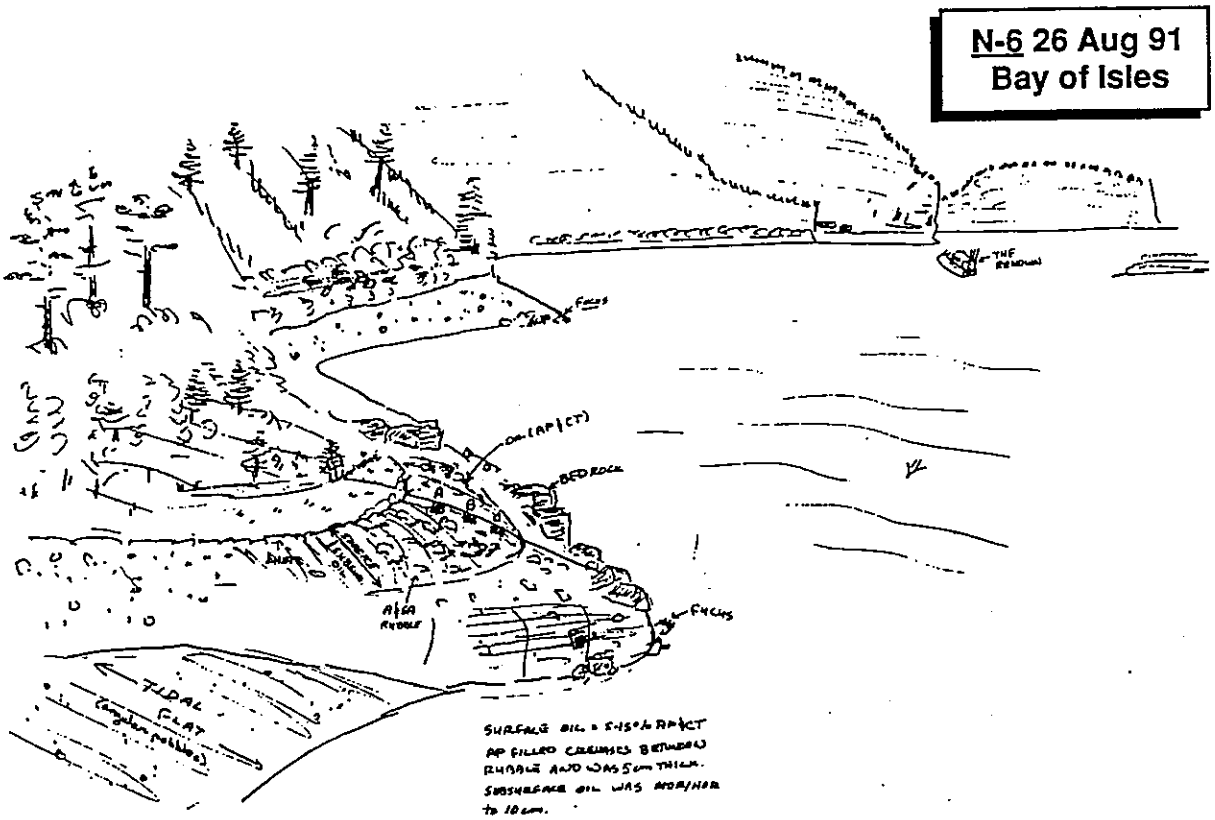


Figure 37. Field sketch of station N-6 on 26 August 1991. Note the presence of surface and subsurface oil in the upper intertidal zone.

During our return visit to station N-6 on August 26, 1991, the following important observations were made:

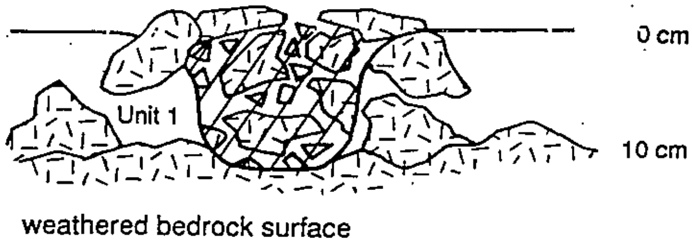
1) Subsurface oil remained in abundance. Asphalt pavement filled crevices between the larger clasts and was 5 cm thick. Subsurface oil in the finer weathered rock debris occurred as medium to heavy oil residue to depths of 10 cm. The three trenches described at the site are shown in Figure 38 and a photograph of the asphalt pavement under the large clasts on the bedrock surface is shown in Figure 39B.

2) The tops of the bedrock and large clasts continue to be cleaned slowly by natural processes. Surface oil coverage was down to 5 to 15 percent asphalt pavement and coat in between the larger clasts, as compared with 40 to 45 percent on May 31, 1990. A photograph of the surface at the high-tide line is given in Figure 39A.

N-6 BAY OF ISLES, 26 August 1991

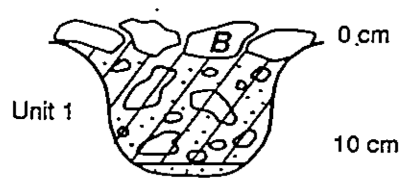
- Oiled Zone

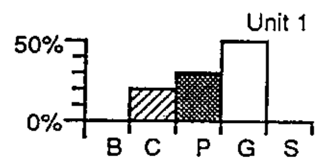
TRENCH A



Unit 1: Very angular clasts with greasy brown oil, moderate to heavy, asphalt-like. Sampled 0-10cm (1B).

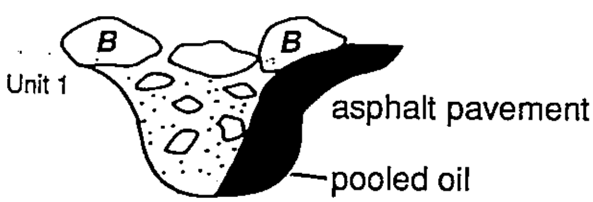
TRENCH B





Unit 1: Heavy oil residue 0-10cm, below stained surface veneer of cobbles and boulders.

TRENCH C



Unit 1: Tight, silty and sandy matrix with angular, platy cobble/pebble clasts. Pooled oil was subsurface expression of small asphalt pavement below surface boulders.

Figure 38. Description of trenches dug at station N-6 on August 26, 1991. Subsurface oil and/or asphalt pavement was present in all of the trenches. See Figure 37 for trench locations.

Figure 39. (Facing Page) Photographs of station N-6 on 26 August 1991.

A. Surface oil near the high-tide line. Note spruce needles stuck in the oil. Photo by M. Hayes.

B. Asphalt pavement under the large clasts scattered over the surface of the bedrock. Photo by J. Michel.

A.

B.

Rocky Rubble Slopes with Raised Bay Bottoms

Two of the stations visited during the August 1991 summer monitoring survey, N-5 (Snug Harbor) and N-13 (Herring Bay), are representative of many of the more protected embayments within PWS that contain steeply sloping, rocky rubble shorelines that are rarely affected by significant wave action. Because of the uplift during the 1964 earthquake, many of these rocky rubble slopes have attached, flat bay bottoms that are exposed during low spring tides. These stations tend to have thicker sediments at the high-tide line than those stations classified as sheltered rocky shores. Therefore, oil penetrated deeply into the subsurface at sites where the sediments were loosely packed. Many of these sites will retain their subsurface oil for a long time.

As indicated by the field sketch of station N-13 in Figure 40, the sediments on these shorelines change from coarse to fine in an offshore direction. This is a result of the coarse material being derived as rubble that has accumulated at the base of the steep slope behind the shore. Our observations at station N-13 show that oil has penetrated deeply into and persisted in the subsurface sediments even where the groundwater discharge is high. Photographs of the heavy subsurface oil in the two trenches dug at this station are given in Figure 41.

Station N-5 in Snug Harbor was not oiled as heavily as station N-13 and the rubble is quite large with little other sediment accumulation. The surface oil occurred as a band on the rubble and there was no subsurface oil penetration. As of the August 25, 1991, survey, the remaining oil occurred as widely scattered patches of asphalt pavement in crevices between the large clasts. It will be interesting to compare the chemical composition of the surface residue at this site with similar sites that were bioremediated, to determine the effects of 2.5 years of weathering.

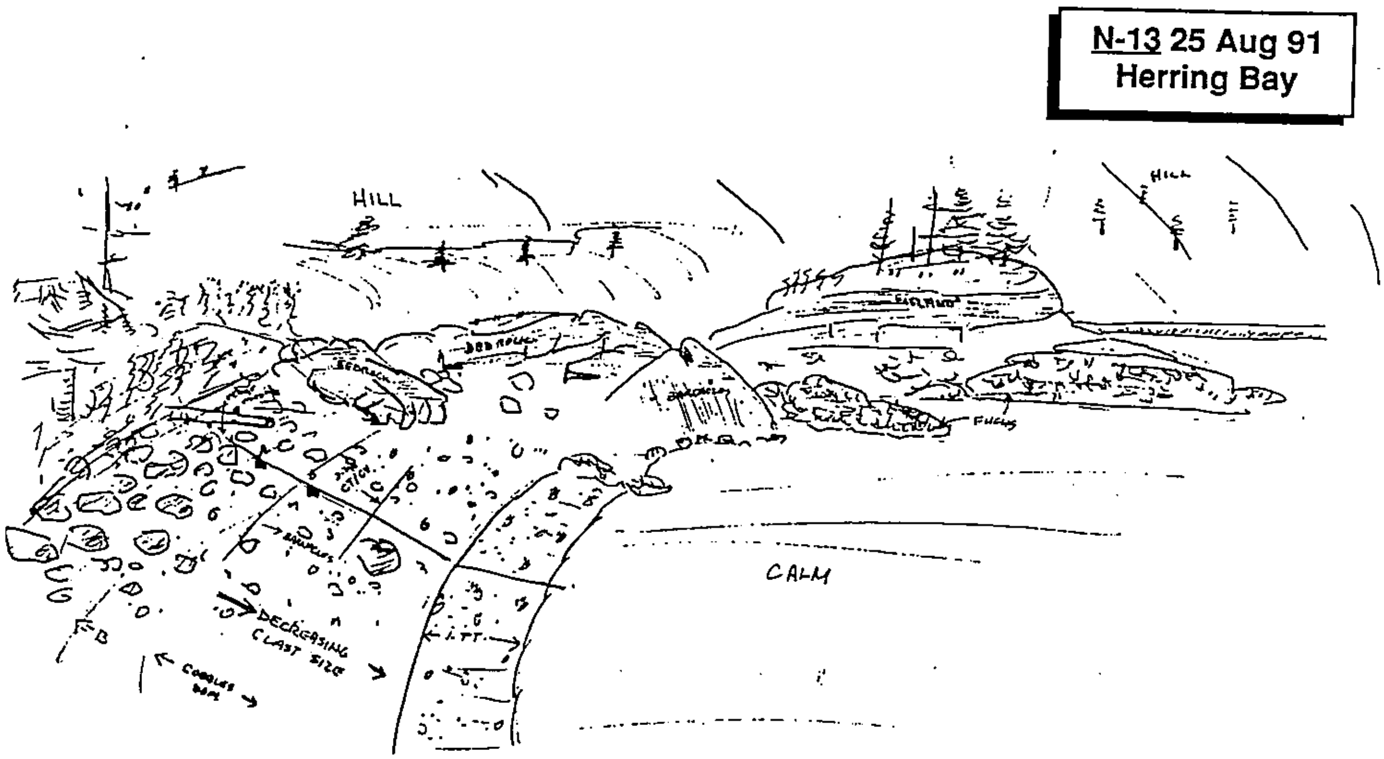


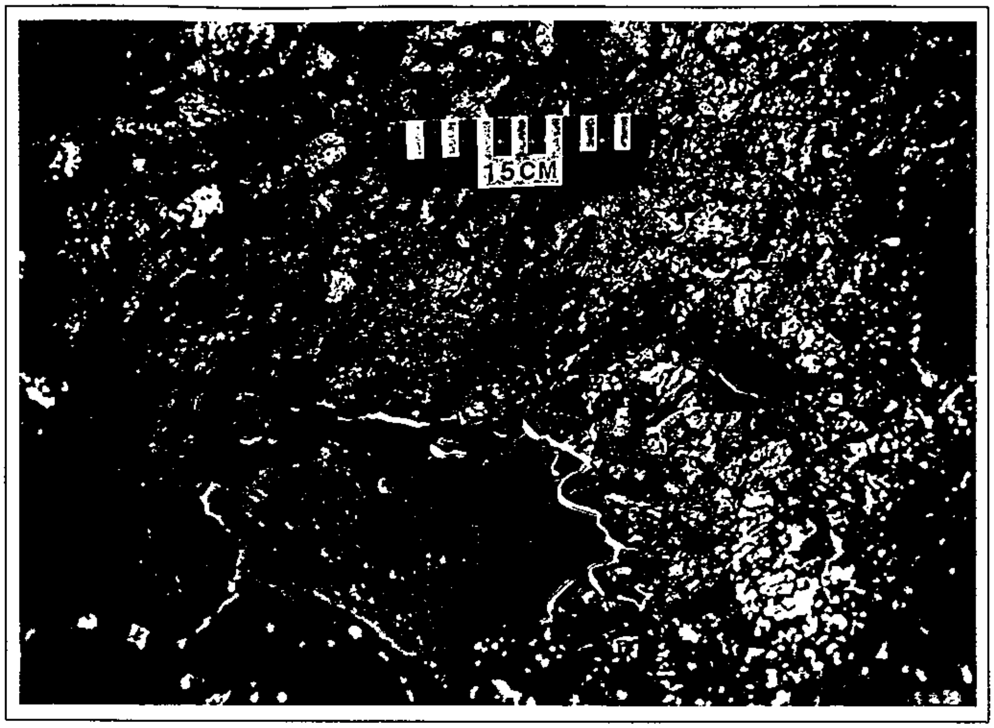
Figure 40. Field sketch of station N-13 on August 25, 1991. Note decrease in grain size in an offshore direction.

Figure 41. (Facing Page) Photographs of station N-13 on August 25, 1991.

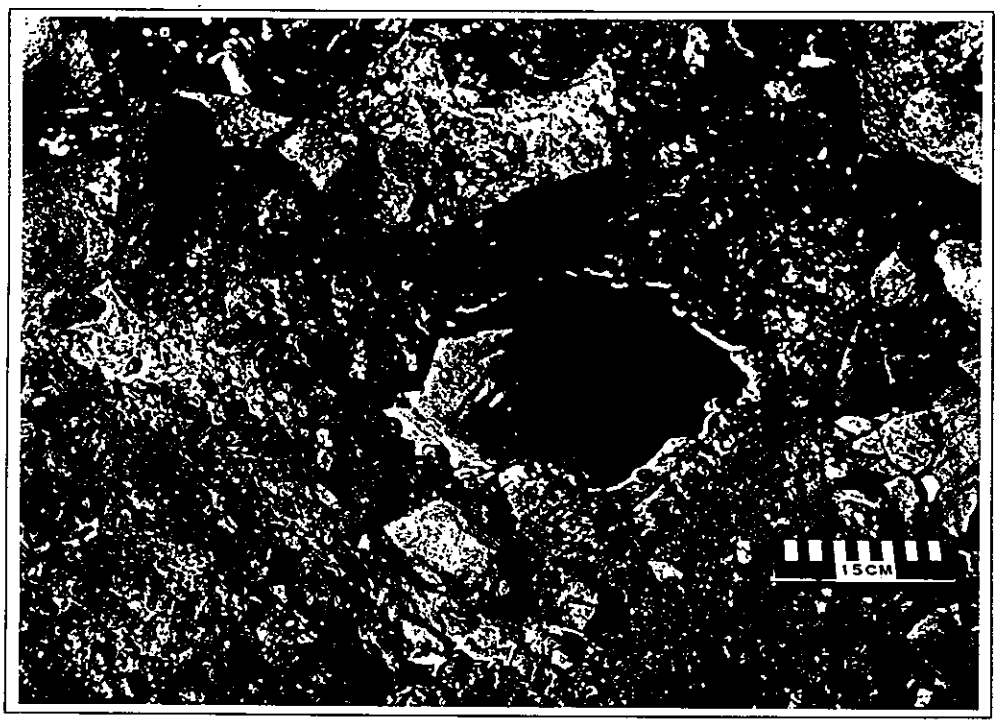
A. Trench A (see Figure 40 for location). Note heavy oil on the water's surface in bottom of trench. Photo by J. Michel.

B. Trench B. Note oil under rubble and on the water's surface. Photo by M. Hayes.

A.



B.



Chapter 3

RESULTS AND DISCUSSION OF CHEMICAL CHARACTERIZATION

Introduction

Since September 1989, NOAA has collected sediment samples from the 18 monitoring stations in PWS for chemical analysis. All of these samples were analyzed for TPH, with results reported in this and previous reports (Michel and Hayes, 1990). A subset of these samples has been analyzed by GC/MS for detailed characterization of the residual oil, with emphasis on the PAHs because they represent the greatest threat of chronic toxicity to intertidal communities and the potential for bioaccumulation.

The analyses conducted by LSU targeted a specific list of PAHs that are either of biological concern or good indicators of weathering patterns in Prudhoe Bay crude oil. The Appendix lists the specific PAHs targeted and the results on concentration for each August 1991 sample analyzed. Table 2 lists the key for the PAH abbreviations used throughout the figures. It should be noted that the total targeted PAHs constitute about 1.7 percent of the reference oil. Total PAHs in Prudhoe Bay crude are much higher, comprising 20 to 30 percent of the oil.

The targeted PAHs include both "petrogenic" compounds, which come from petroleum products, and "pyrogenic" compounds, generated by the combustion of fossil fuels. Pyrogenic PAHs are ubiquitous, but are most common in sediments from urban areas because of non-point source runoff from highways and fallout from power plants. Chemical data from PWS sediments and biota collected in the 1970s and early 1980s showed that background concentrations of PAHs were extremely low.

It is difficult to discuss data on PAH concentrations and distributions in environmental samples. There are 37 different compounds in the targeted set of PAHs, with concentration data for each compound and PAHs targeted. The objective of the detailed chemical characterization is to track weathering patterns and relative rates among the different types of residual oil. We use the distribution patterns in the PAHs to track changes in the oil as it weathers. The best way to show distribution patterns for samples with widely varying concentrations is to plot them as relative concentrations. Figure 42 shows the distribution of PAHs in the reference oil, plotted as the relative concentration, normalized to the most abundant PAH present. That is, all the individual PAH concentrations are divided by the concentration of the single PAH that has the highest value. For the reference Prudhoe Bay crude oil, C-2 naphthalene is the most abundant PAH, so in Figure 42, C-2 NAPH is plotted at a normalized value of 1.0. This convention allows for ready comparison of the weathering patterns among samples, regardless of the absolute concentration in the samples.

Table 2. Key for the PAH abbreviations used on Figures 42 through 50.

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

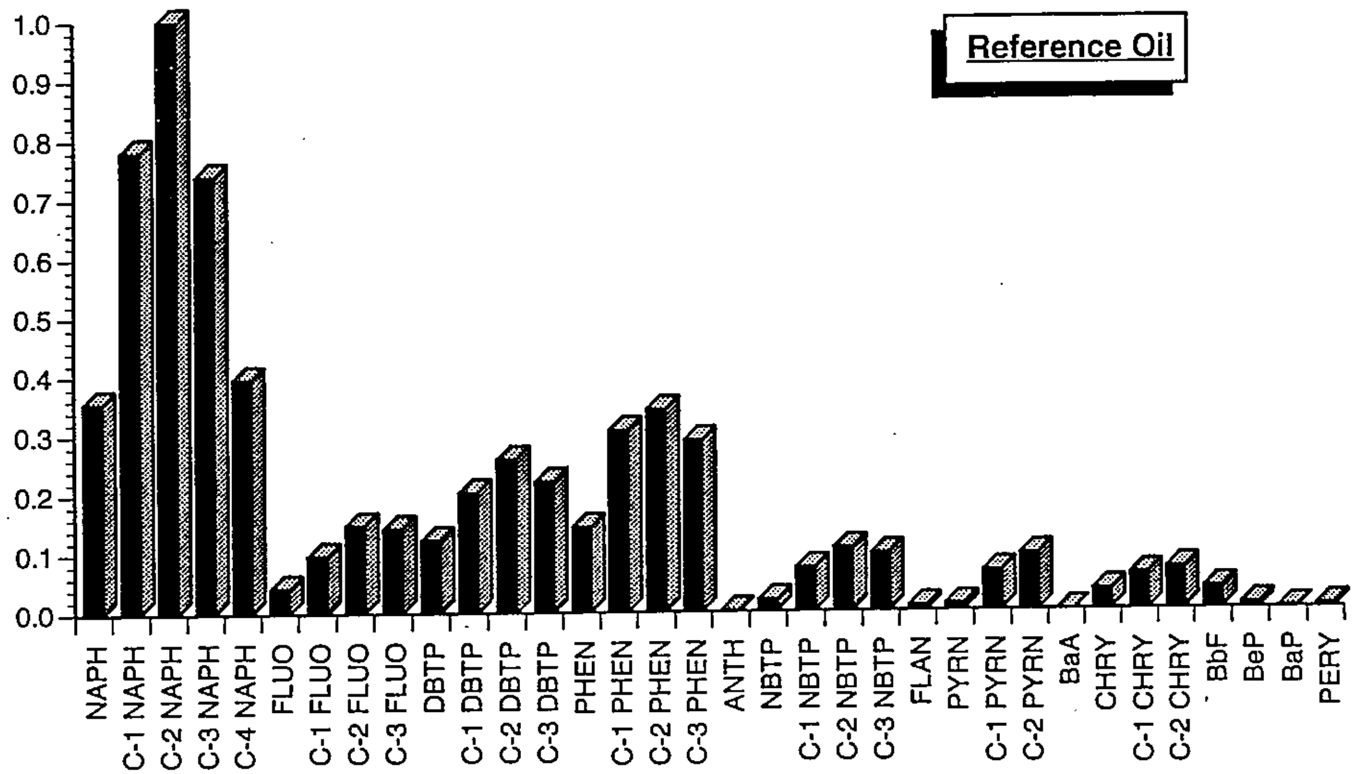


Figure 42. Plot of normalized PAH distribution for reference oil—Prudhoe Bay crude.

An understanding of the PAH pattern in the reference oil is critical to interpretations of similar plots for sediment samples taken over the period September 1989 to August 1991. The reference oil is the template against which visual comparisons can be made to assess the degree of weathering undergone by the spilled oil under different conditions.

The PAH distribution in the reference oil can be discussed in terms of the relative amounts of the major groups of compounds, called homologous series, which consist of a parent aromatic compound, such as naphthalene, and similar compounds where one or more of the hydrogen atoms in the ring structure are replaced with an alkyl side chain. Therefore, in Table 2, parent naphthalene is followed by four alkylated homologs that contain from one to four alkyl substitutions, which are designated with a number after the carbon symbol to reflect the degree of alkylation. For Prudhoe Bay crude oil, the amount of the parent compound in each of these series is always the lowest, and the relative concentration of each of the alkylated compounds increases with increasing alkylation for the first two compounds, followed by a decrease. Thus, the C-2 homolog in each series is the highest.

Prudhoe Bay crude also has naphthalenes as the most abundant PAHs, followed by phenanthrenes. Dibenzothiophenes are only slightly less abundant than the phenanthrenes, and slightly more abundant than the fluorenes. The relative amounts of dibenzothiophenes are important to track because they can be more slowly degraded than the non-sulfur bearing PAHs. Finally, note the very low concentrations of pyrene and chrysene, high-molecular weight PAHs that are very slow to weather.

One other note of caution in interpreting the PAH plots is warranted. There can be a tremendous amount of variation in the oil concentration and composition over very small distances. The effectiveness of nutrient addition as part of the shoreline treatment strategy was extremely difficult to evaluate because the high intrasite variability made comparisons of the oil loading versus time between treated and control sites appear statistically the same. According to a 1992 Exxon handout on bioremediation effectiveness, "The key proof–direct measures of changes in oil composition to show loss of oil by degradation–was lacking," for the set of samples from 1990 fertilized versus control beaches. The chemical characterization results should be interpreted with this degree of variability in mind. The samples represent discrete intervals at a single location, not composites. It is likely that the variability is diminishing over time, as the residual oil weathers to a more uniform endpoint.

Weathering Patterns of the Residual Oil

Cobble-Boulder-Platforms with Berms

There was a clear relationship between the rate of removal of subsurface oil from these beaches and the rate of weathering as shown in the PAH plots. On beaches with large amounts of residual oil adhering to the sediments, the PAH patterns are dominated by the relatively unweathered fraction of the oil that remains. Microbial degradation is a surface-active process; thus, a globule of oil attached to a sediment grain would be a mixture of highly degraded surface material and less degraded core material. This differential rate of weathering is particularly important for very coarse-grained sediments, where the oil dominantly occurs as globules attached to a small surface area of sediment, as opposed to the high surface area of fine sand and mud.

As of August 1991, weathering of the residual oil had progressed the most at stations N-1 at Point Helen, N-4 on Smith Island, N-7 on Knight Island, and N-17 on Perry Island. Figure 43 shows the PAH plots for samples from the upper platform at depths of 35 to 55 cm below the surface for January and August 1991. TPH values for these sediments were 590 mg/kg (January) and 820 mg/kg (August). This oil is highly weathered. There has been complete degradation of both the naphthalenes and fluorenes. The lighter compounds in each series have been removed. At N-1, the sediments are composed of very large boulders and cobbles on a bedrock platform. The voids are not packed with finer sediments (the trench descriptions show no granule or sand-sized sediments); thus, there is good tidal flushing and the interstitial water completely drains at low tide. These processes aided in the rate of weathering after some of the oil was removed by physical processes.

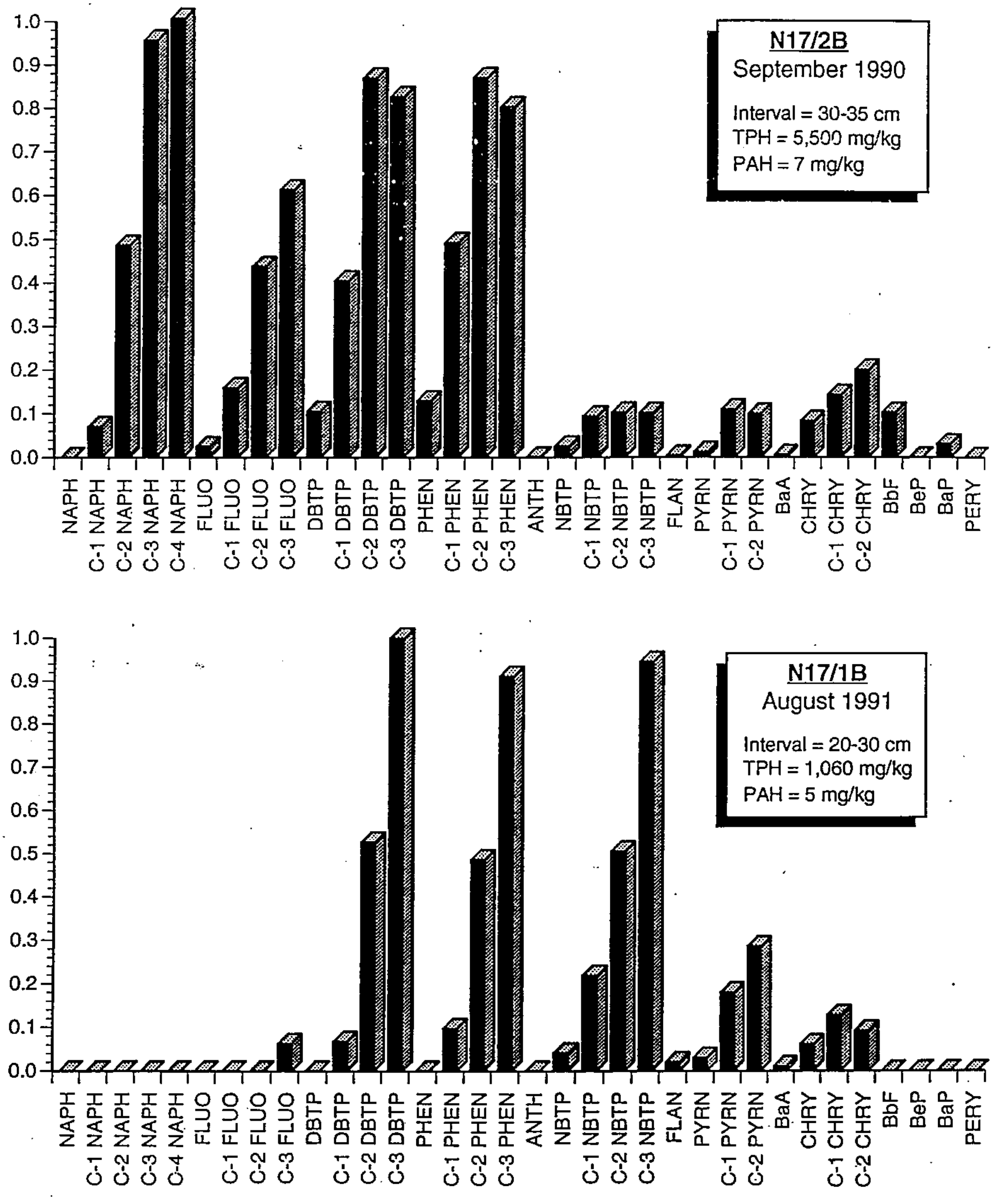


Figure 43. Plots of normalized PAH distributions in sediments from the upper platform at N-1 on Point Helen in 1991. Sediments were collected from 35 to 55 cm depth. TPH values were: 590 mg/kg (January) and 820 mg/kg (August).

By August 1991, the subsurface oil at N-17 on Perry Island was also heavily weathered. Figure 44 shows the PAH plots for subsurface samples collected in September 1990 and August 1991. The September 1990 samples show the influence of less weathered oil introduced into the intertidal zone by berm relocation. The sediments were visibly black, containing 5,550 mg/kg of TPH. In comparison, the August 1991 sample contained an oily film and had a TPH of 1,060 mg/kg, and the targeted PAHs totaled 5 mg/kg. The PAH pattern shows extensive degradation, with nearly complete removal of the naphthalenes and fluorenes, and loss of the lighter compounds in each series. The sulfur-bearing compounds dominate the remaining PAHs. This site is backed by a small lagoon; high rates of groundwater flow were always observed. The groundwater most likely played an important role in both physical removal and higher degradation of the subsurface oil.

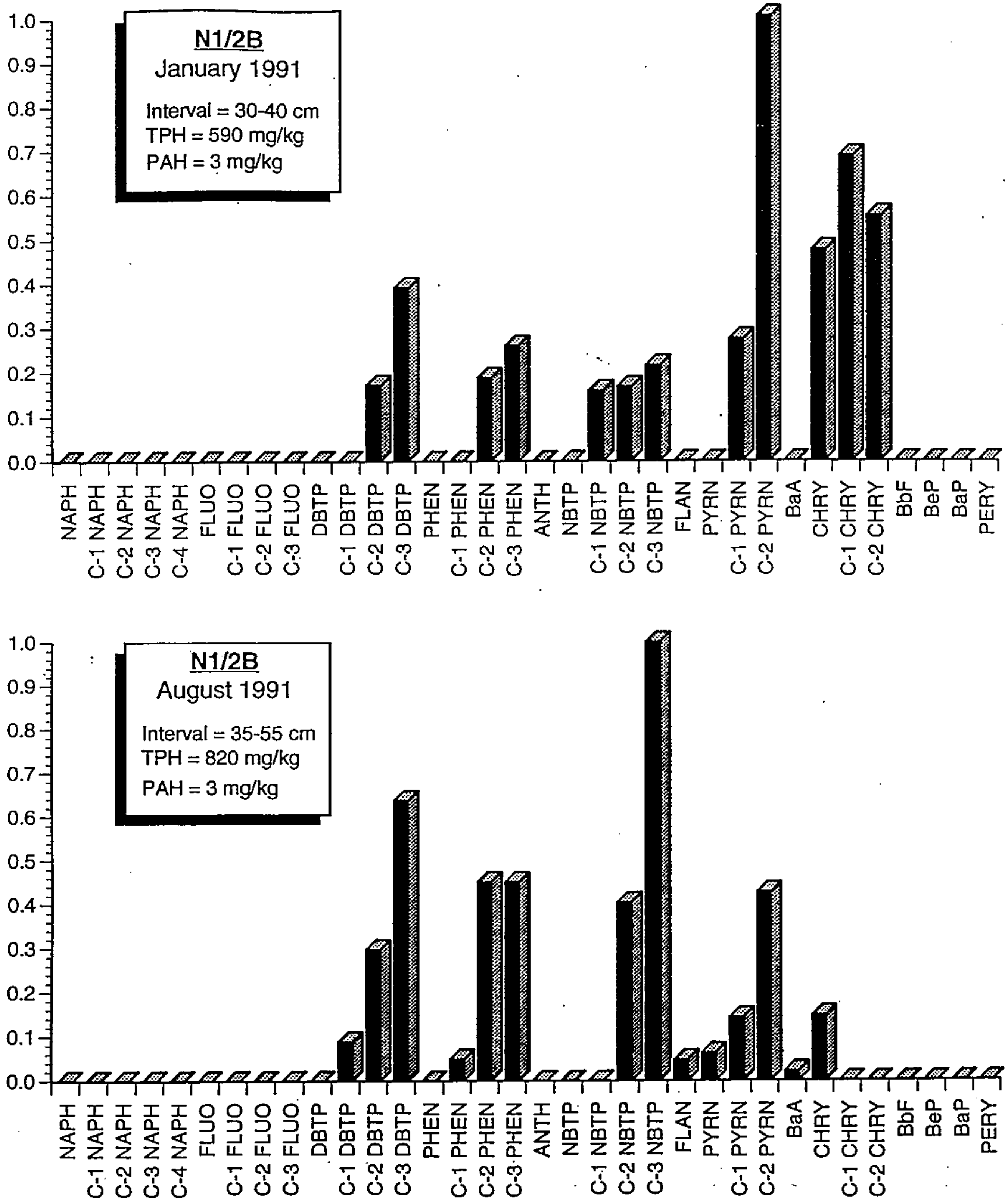


Figure 44. Plots of normalized PAH distribution in sediments from the upper platform at N-17 on Perry Island in September 1990 (upper) and August 1991 (lower).

Station N-7 was one of the 1990 monitoring sites for the bioremediation effectiveness studies in PWS (Prince et al., 1990). In 1990, Station N-7 received applications of Custombien on May 30 and July 13 and Inipol on September 8. Very high concentrations of subsurface oil have persisted, with values of 6,480 to 14,750 mg/kg measured in August 1991. However, the PAH plots in Figure 45 from two different sites in the upper platform, show that the remaining oil has undergone moderate weathering. Most of the naphthalenes and fluorenes have been removed. Phenanthrenes are still present, but the dibenzothiophenes now dominate the PAHs. Total targeted PAHs were 120 mg/kg, representing the same proportion of targeted PAHs in the reference oil (about 1.7 percent), indicating that there has been degradation of all components of the oil.

The PAH plots for N-3 on Smith Island's two cobble-boulder stations showed evidence of an intermediate degree of weathering, and there was still moderate to heavy amounts of subsurface oil at depth in the upper platform (4,670 to 12,520 mg/kg; Table 1). The PAH plots for sediment collected in August 1991 are shown in Figure 46; targeted PAHs totaled 120 mg/kg for 1B and 900 mg/kg for 3B. The higher sample (1B) shows extensive weathering; similar in pattern to samples collected from the high-tide berm in September 1990. However, weathering rates lower down the beach are slower and the TPH is 50 percent higher. Sample 3B (Figure 46) can be characterized as moderately weathered; the naphthalenes and fluorenes have been significantly reduced, but are still present. The naphthobenzothiophenes are still a minor component compared to the phenanthrenes and dibenzothiophenes. The targeted PAHs form over 10 percent of the oil, an enrichment of a factor of 6, indicating that the PAHs are degrading more slowly than the rest of the oil components.

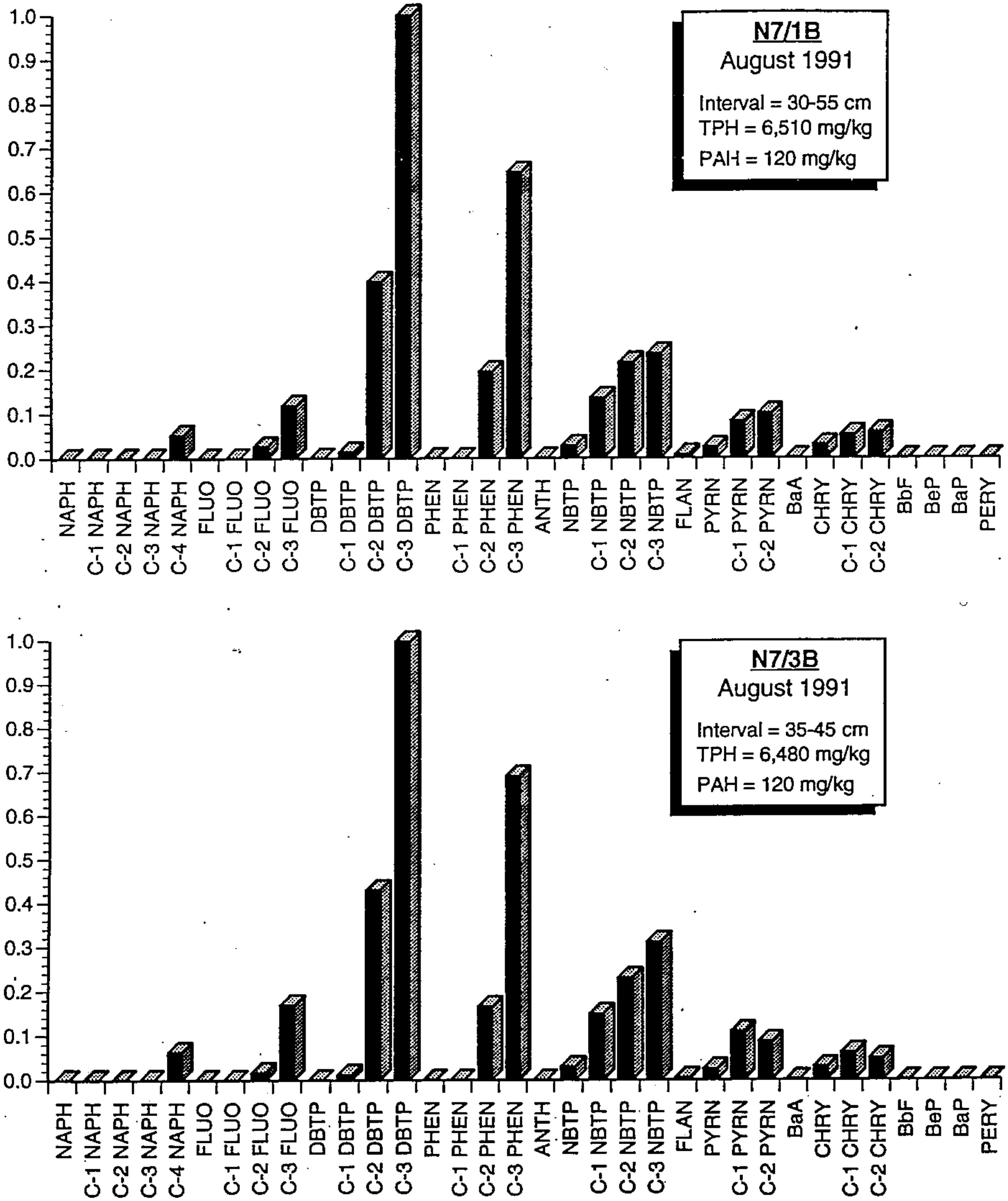
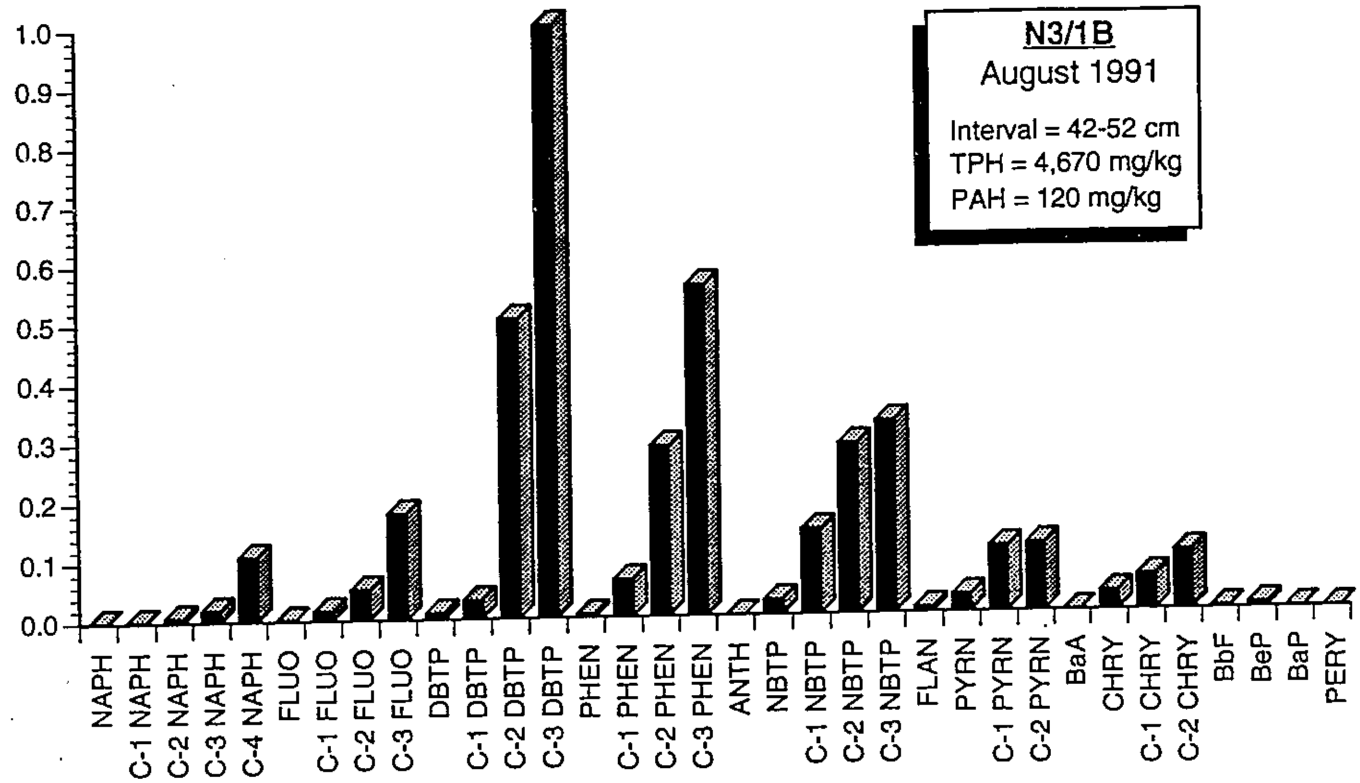


Figure 45. Plots of normalized PAH distribution in sediments from trench B (upper) and trench D (lower) in August 1991 for N-7.



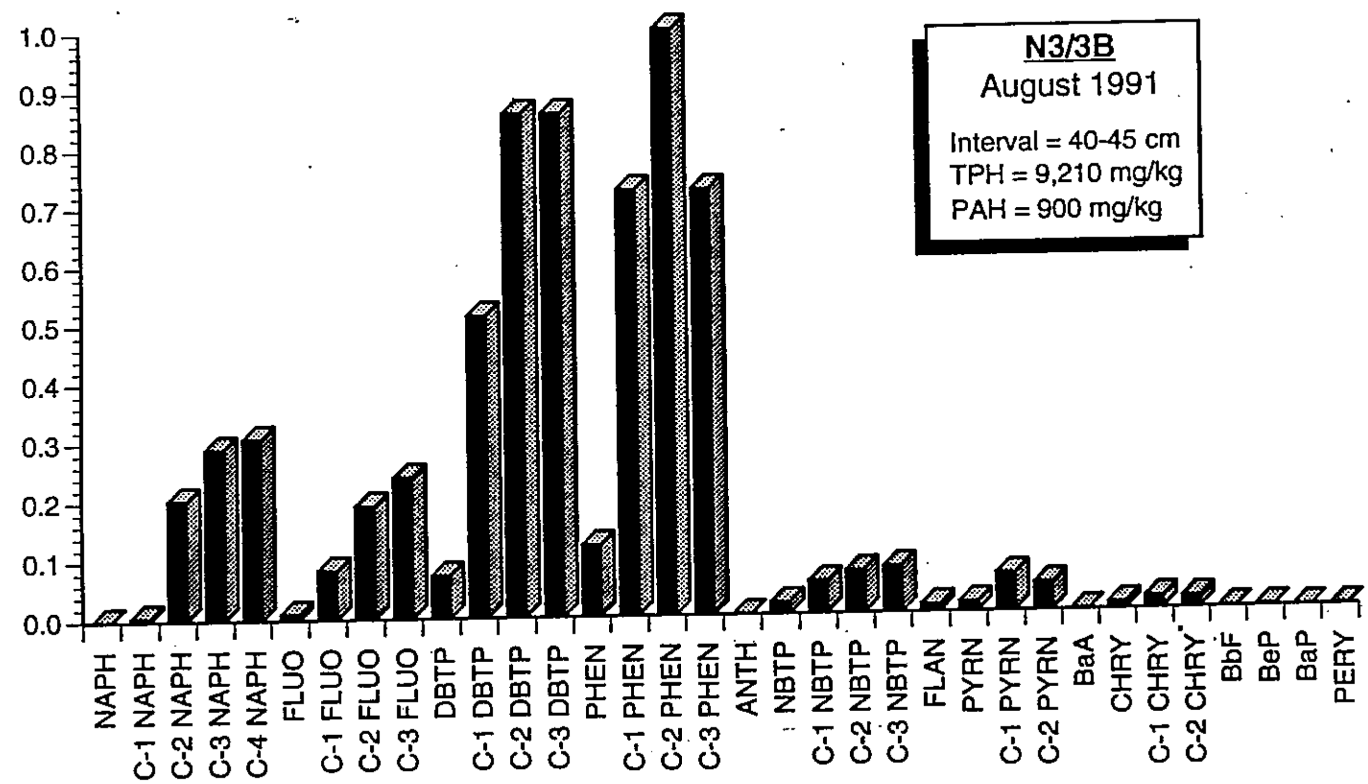


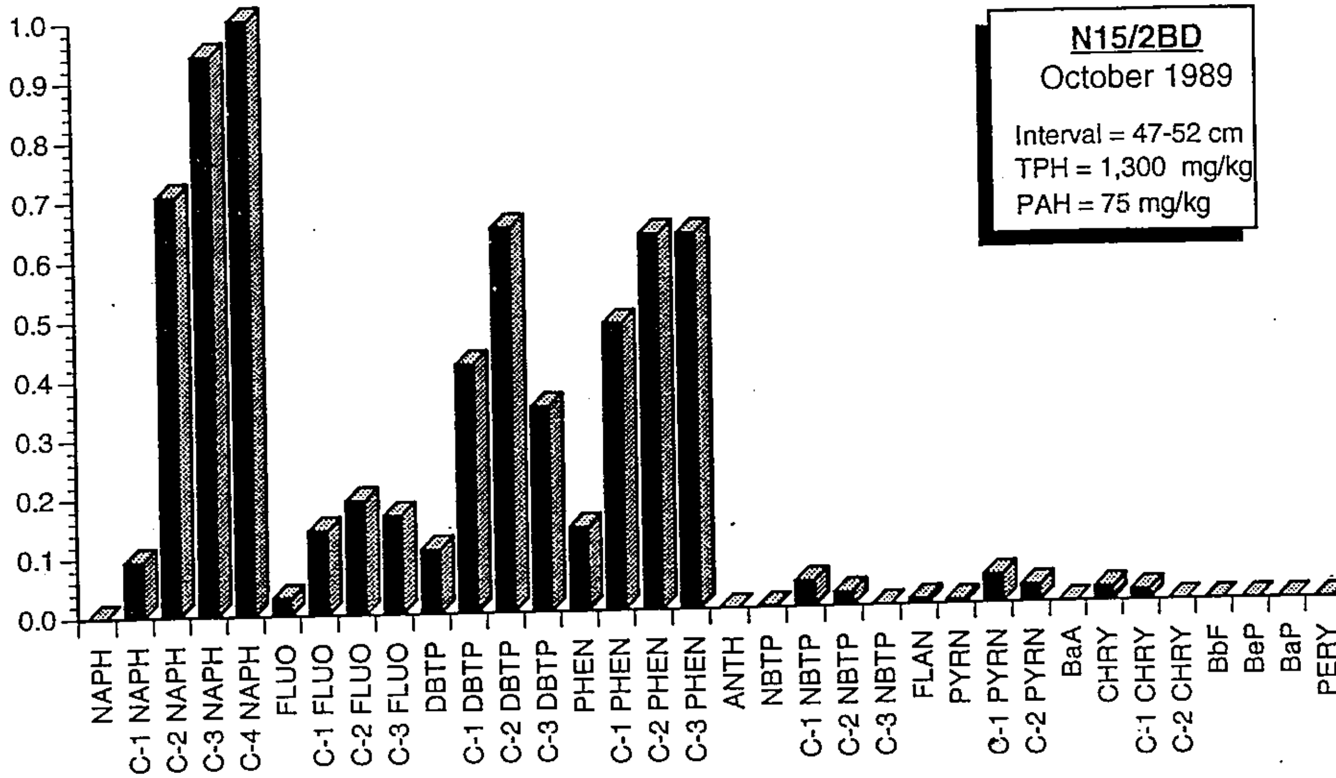
Figure 46. Plots of normalized PAH distribution in sediments from the upper platform on Smith Island in August 1991 in trench B (upper) and trench D (lower).

The subsurface oil at N-15 on Latouche Island has undergone extensive weathering after tilling and relocation of the sediments, followed by fertilizer application. The zone of heavy oiling below the cobble veneer had not weathered to any degree. Figure 47 shows the PAH plots for sediments from October 1989 and a sample of sediments with a greasy oil coating for the interval 35 to 45 cm in August 1991. By October 1989, weathering had progressed primarily by evaporation of the lighter components. Note that by August 1991 the naphthobenzothiophenes are the dominant PAH, indicating extensive removal by microbial degradation (compare Figure 47 with Figure 42, the reference oil). Total targeted PAHs were 8 mg/kg.

Rocky Rubble Slopes

Chemical characterization data are available for two stations in this class: N-5 and N-13, which are set-asides. It is unfortunate that we do not have good treated comparisons for these stations, because their PAH patterns are very interesting. Figure 48 shows the PAH plots for N-13, comparing samples collected in September 1990 and January and August 1991. This site has shown the least amount of weathering observed at any of our stations. Prior to August 1991, the samples showed only slight to moderate weathering, with removal of the lighter members of each series, but with naphthalenes still dominating the PAHs. As of August 1991, the phenanthrenes dominate, but there are still significant amounts of the heavier naphthalenes and fluorenes present. The subsurface oil at this very sheltered site is only moderately degraded after three summers of weathering.

The shallow samples at N-5 show a similar pattern of slow weathering rates. Figure 49 shows the PAH plots for samples collected in September 1990 and August 1991. There have been only small changes over this period. The phenanthrenes and dibenzothiophenes are about equal, and the C-1 homolog in each series is still present. The naphthobenzothiophenes are still a minor component of the targeted PAHs, which total 50 mg/kg.



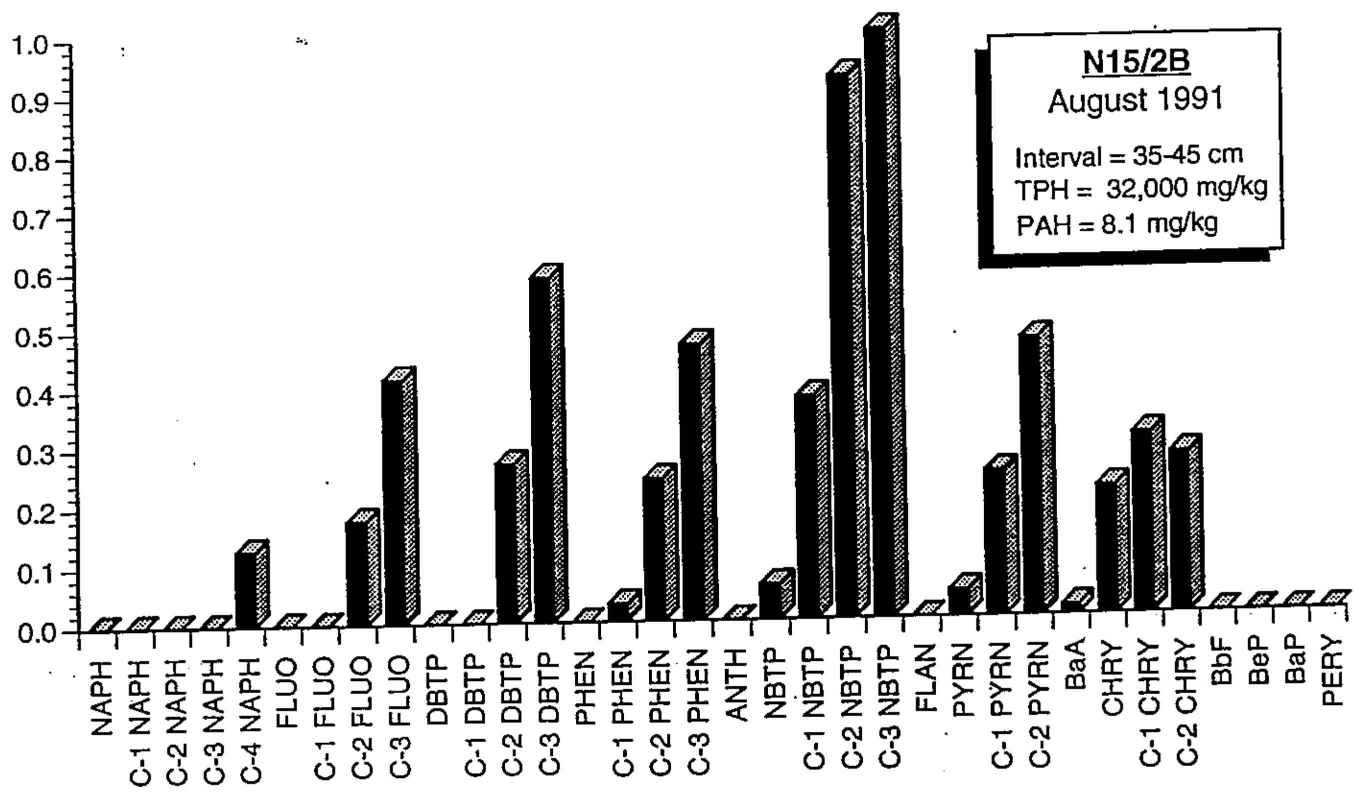


Figure 47. Plots of normalized PAH distribution in sediments from the upper platform at N-15 in October 1989 and August 1991.

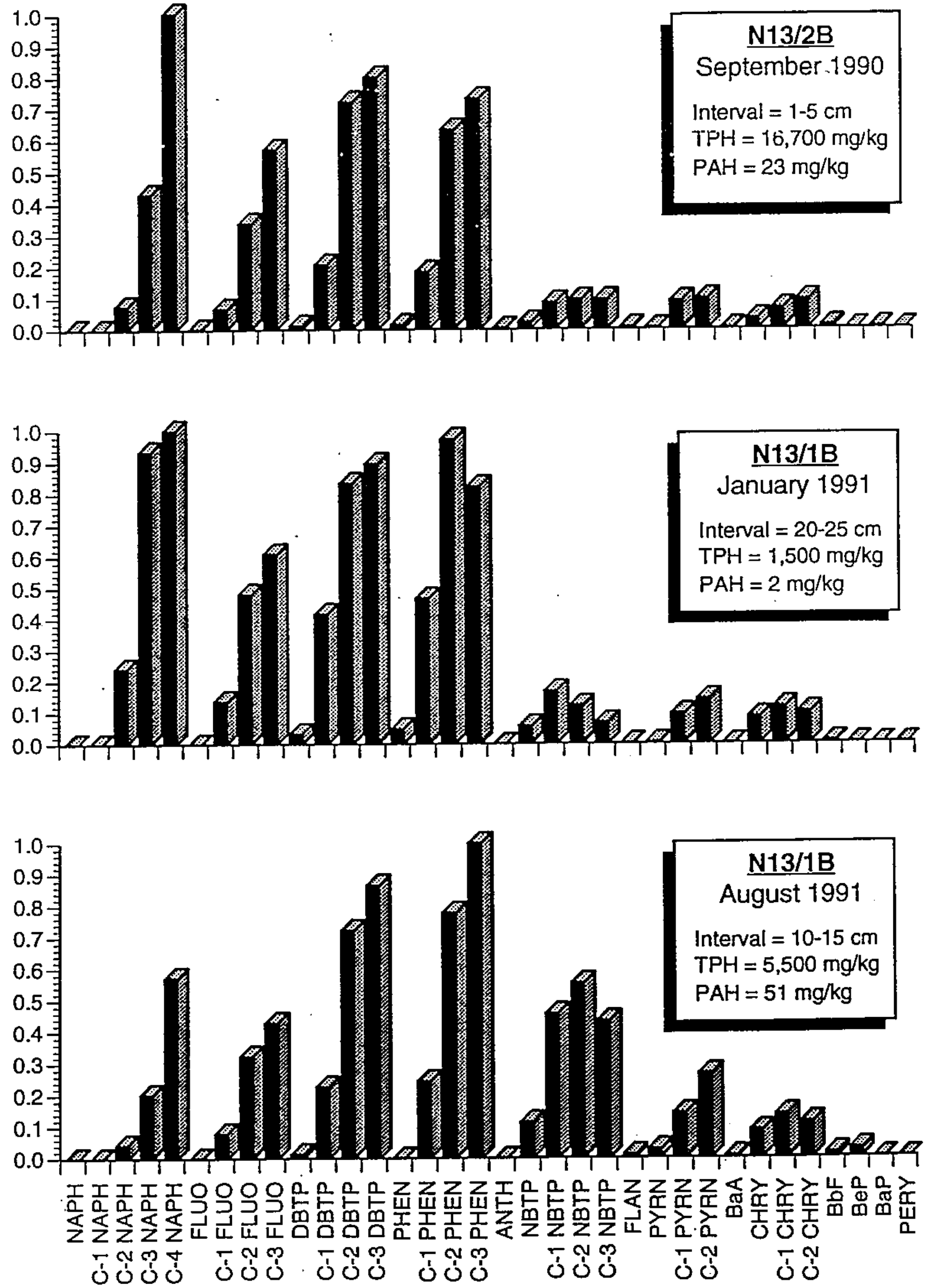


Figure 48. Plots of normalized PAH distribution in subsurface sediments from N-13 for September 1990, January 1991, and August 1991.

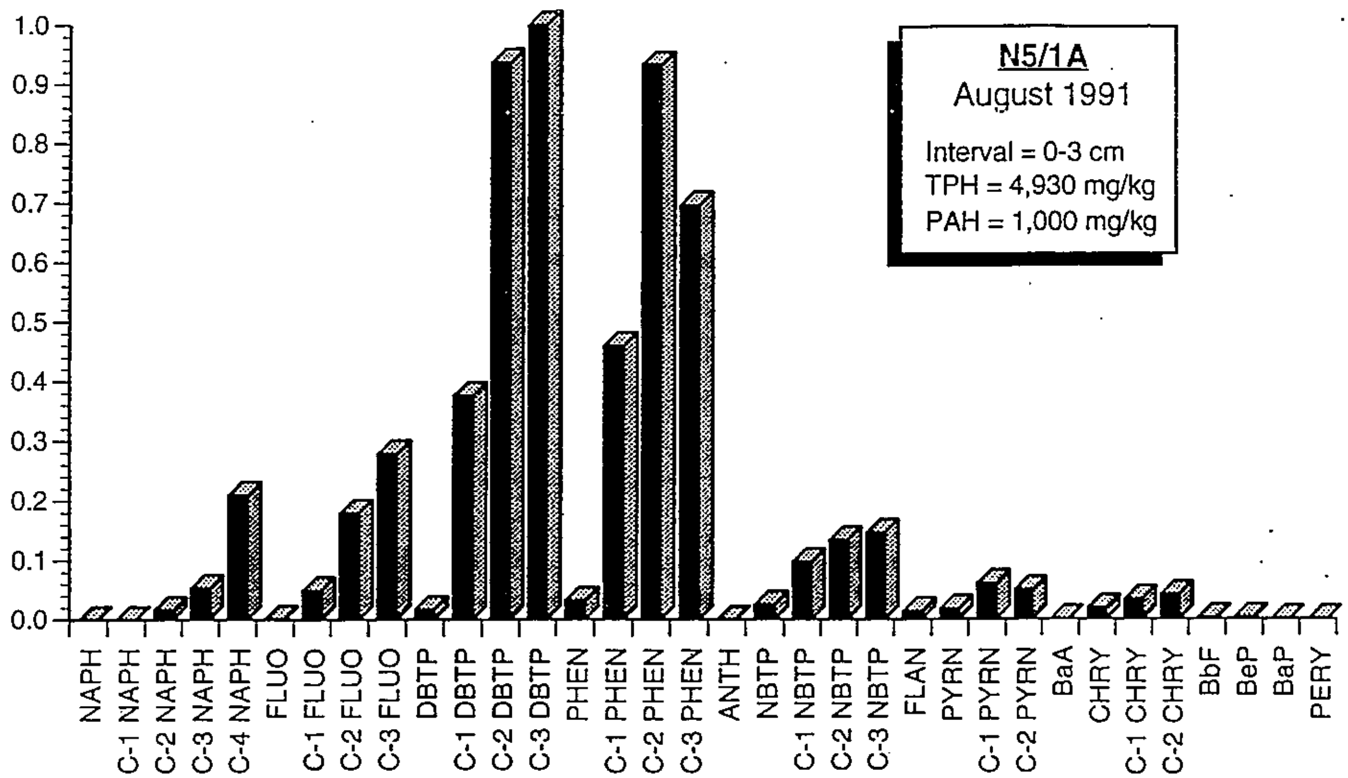
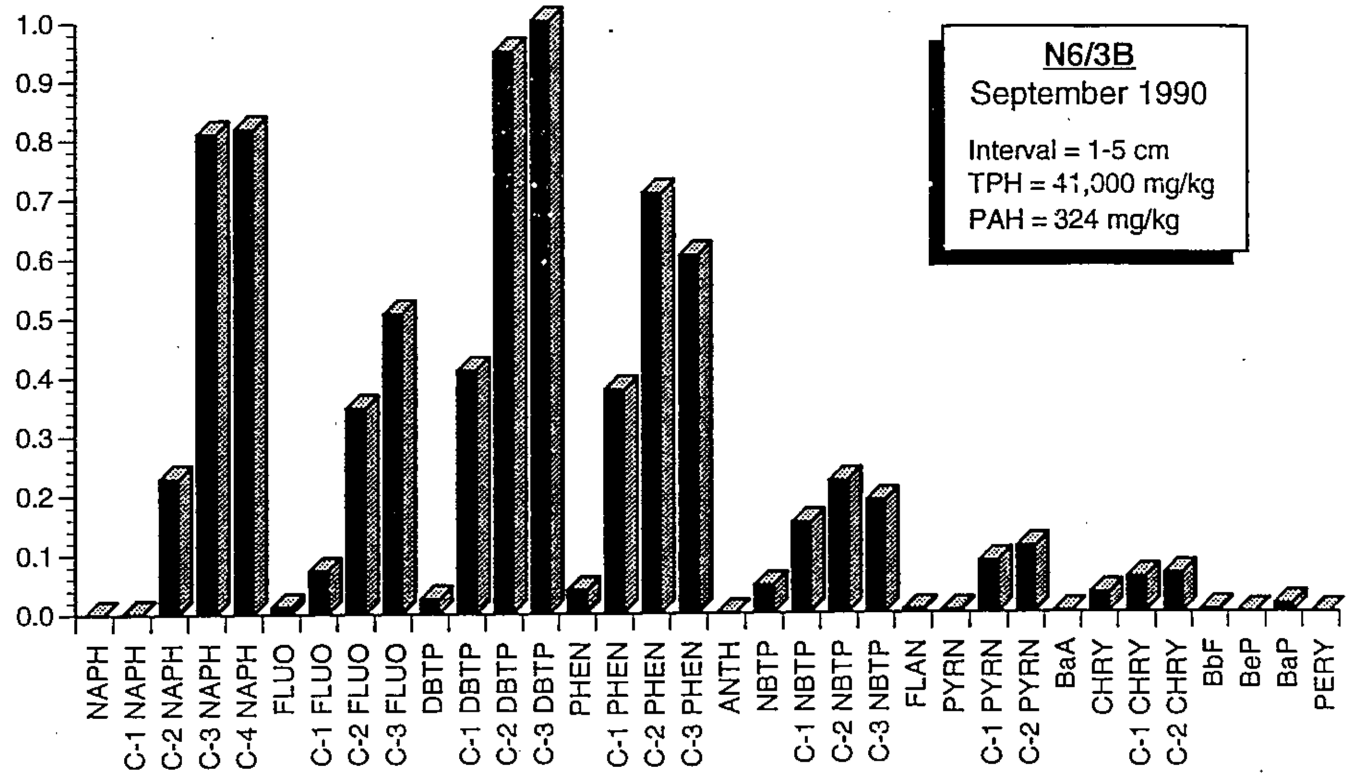


Figure 49. Plot of normalized PAH distribution in sediments from N-5 for September 1990 and August 1991.

Sheltered Rocky Coasts

The heavily oiled sediments at station N-6, a set-aside in the Bay of Isles, have weathered to a moderate degree. Figure 50 shows the PAH plots for samples collected in September 1990 and August 1991. These samples represent the oil that has accumulated under the surface veneer of loose rocks and on top of the bedrock. In the field, it appeared quite greasy and soft (Figure 39B). The plots show some degradation of the residual oil over the 1-year period. The naphthalenes have been removed to the extent that they are less abundant than the two- and three-ringed aromatic compounds. The lighter members of each series have been degraded, up to the naphthobenzothiophenes. These samples have undergone only moderate weathering.



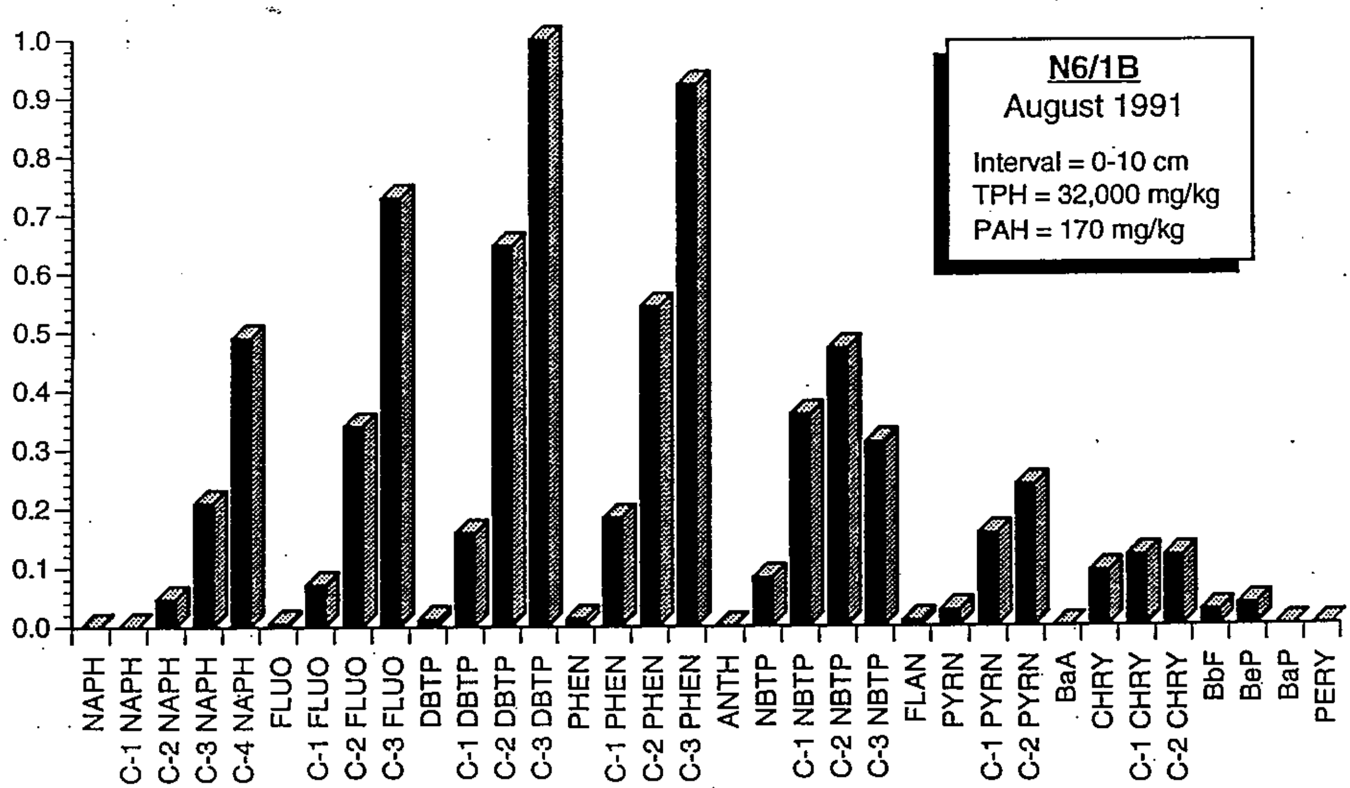


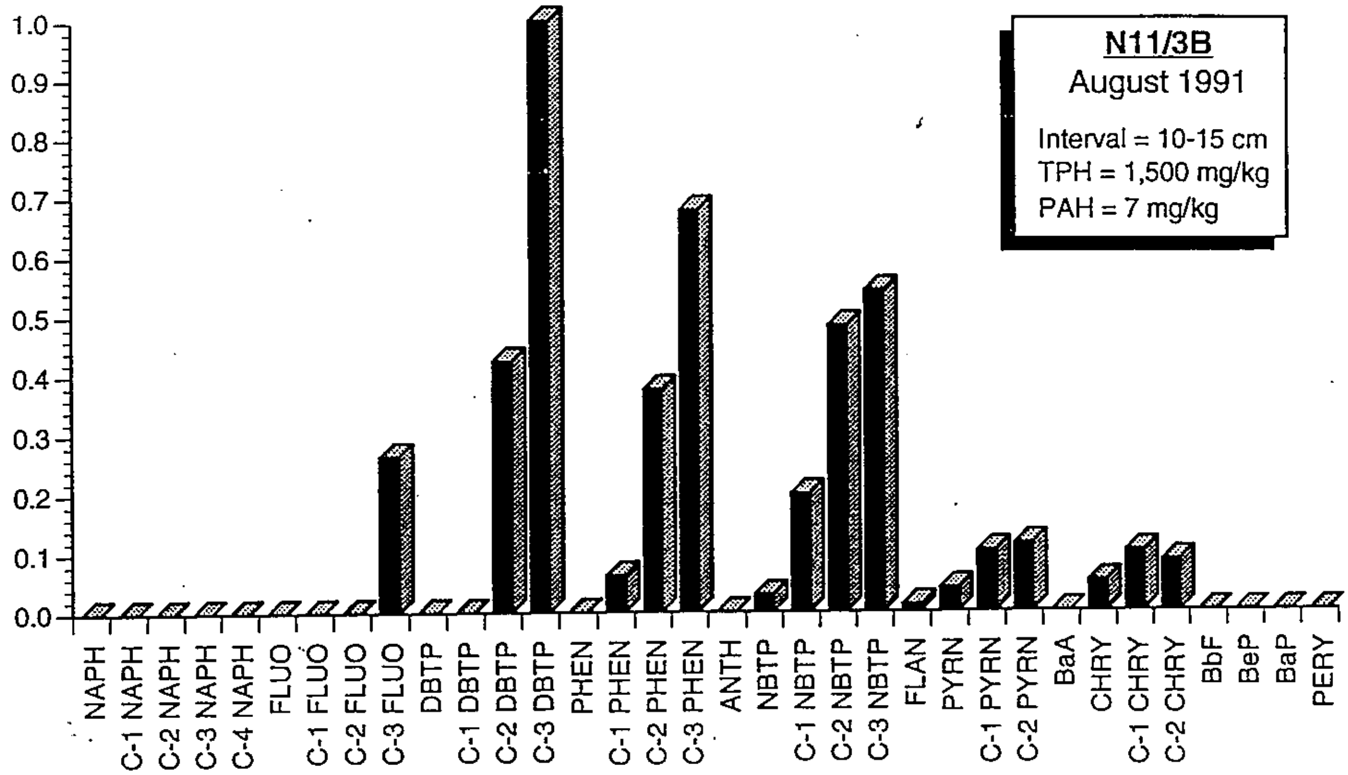
Figure 50. Plots of normalized PAH distribution in sediments from N-6 for September 1990 and August 1991.

At station N-12, the rocky corner in a small bay on Crafton Island, a sample of the incipient asphalt pavement forming on top of the bedrock was sampled in August 1991. Figure 51A shows the PAH plot. Targeted PAHs totaled 680 mg/kg. Weathering has removed the naphthalenes and some of the fluorenes, but very little else. In comparison, a sample of organic rich gravelly sand from N-11, less than 20 m away, has undergone extensive weathering, as shown in Figure 51B. This site has significant groundwater discharge over and through the peaty substrate, which most likely has increased degradation of the oil.

Summary

Characterization of the oil remaining in PWS as of August 1991 is a difficult task because of the high degree of variability. Yet, there are some general trends and conclusions that can be made. The subsurface oil in the cobble-boulder beaches has undergone extensive weathering, even at depth, at most locations. Only the most resistant PAHs remain. Where residual oil concentrations have remained high, e.g., N-3, there has been less weathering. There is a relatively simple relationship in that degradation is a surface-active process, and, where oil residues are thick, the weathering process is slowest for the interior oil. As expected, these thicker oil deposits degrade slowly and remain a threat to intertidal communities for longer periods of time. Efforts that increased the surface-to-volume ratio of oiled sediments have increased degradation of the residual oil. Yet, even with the most intensive shoreline cleanup of gravel beaches ever undertaken, continuing over 3 years, it has taken at least three summer periods for the remaining oil to become heavily weathered in highly porous, cobble-boulder beaches.

The oil residues on rocky coasts are highly variable in nature and thickness; our sampling has focused on the thicker deposits. The chemical results have shown that these thicker deposits have undergone only moderate weathering. Even the two-ringed aromatic compounds are still present. Some of these deposits have formed hard crusts or taken on the appearance of tar; whereas, others are still relatively soft. It is very important to continue sampling these sites, to track the weathering fate of these oil residues.



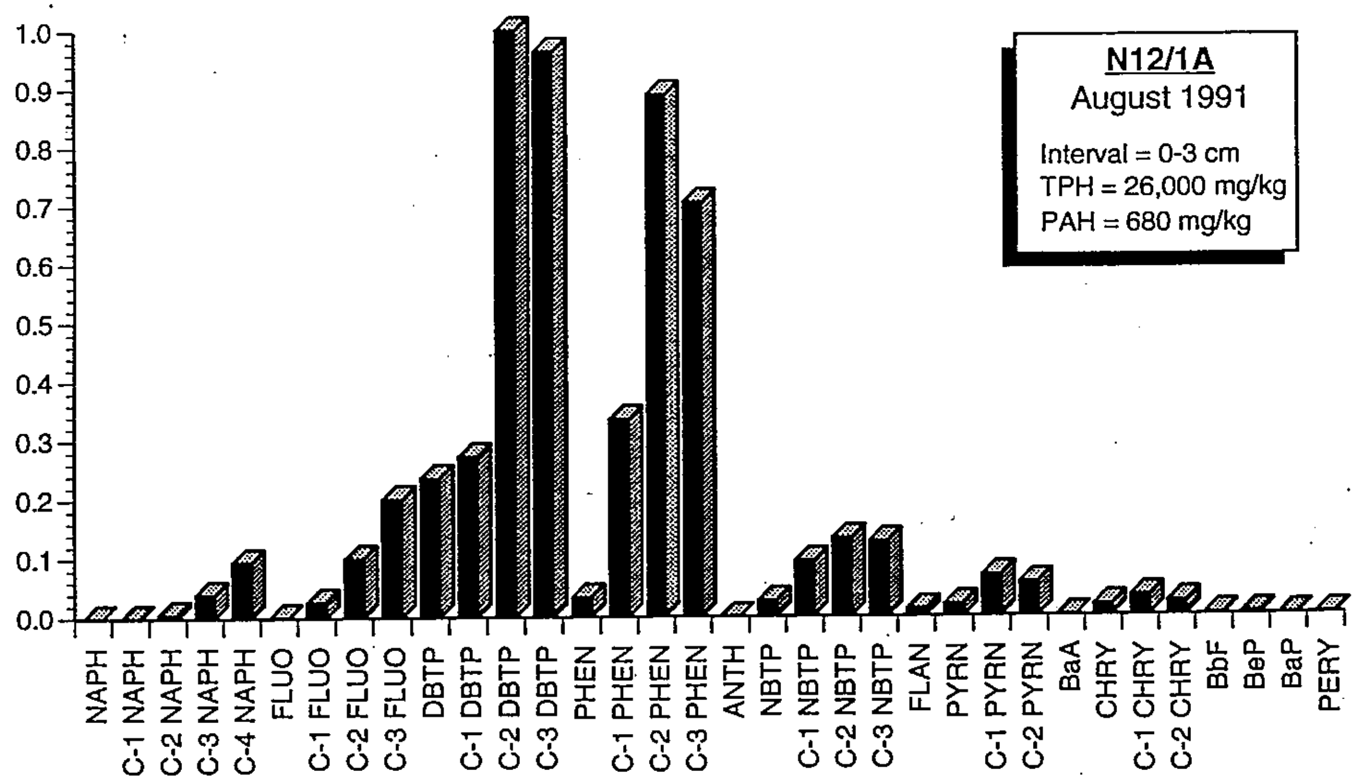


Figure 51. Plots of normalized PAH distribution in sediments from N-11 and N-12 for August 1991.

Chapter 4
THE VALIDITY OF BERM RELOCATION AS A SPILL-RESPONSE TECHNIQUE

Introduction

The application of the berm-relocation technique as a method to aid the removal of subsurface oil was carried out at a scale never before done during the summers of 1990 and 1991 at the *Exxon Valdez* site. During the summer of 1990, berm relocation was carried out at 30 sites along approximately 3,000 m of beach. According to the work plans, relocation activities were to involve "movement of oiled sediments from the inactive beachface areas into the upper intertidal zone, where they could be treated and reworked by wave action" (Exxon, 1991). In practice, there were instances where sediment was deposited on the middle intertidal zone.

NOAA's geomorphological monitoring study, as well as those of Exxon and the State of Alaska, provide an unprecedented opportunity to evaluate the effectiveness of the method. As discussed above, berm relocations were carried out at six of the permanent NOAA stations. Also, eight additional berm-relocation sites were studied during our January 1991 survey. A major report by Exxon (1991), summarizes their findings at most of the berm-relocation sites. They conclude that the berm-relocation process was very effective in aiding the removal of subsurface oil by natural processes. They also concluded that "all the sites have been restored to pre-treatment morphology with no net loss of sediment"; although, we did not find that to be the case at all of our sites.

Results of This Study

It can be stated unequivocally that all the berm-relocation sites we studied showed a marked decrease in subsurface oil in the upper intertidal zone over a period of a few months after the berm relocation was accomplished. The exact responses of the different areas regarding the details of the recovery of beach-profile morphology and sediment distribution patterns, as well as rates of oil removal, were highly site specific. This means that as much site-specific data as possible should be gathered before attempting such projects. Nonetheless, there were several general lessons learned regarding future application of the berm-relocation technique based on our studies in PWS:

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

2) If a large excavation was carried out resulting in the destruction of all high-tide berms and massive volumes of sediment being moved to the middle

intertidal zone, as was done at station N-15 in August 1990, recovery of the profile to its original configuration is considerably slower (more than 1 year). This type of relocation does however, effectively aid in the removal of the subsurface oil. There may be some situations where this technique would be useful.

3) We believe that complete removal of the storm berm, as was done at Point Helen in the summer of 1991, has some inherent problems, including: (a) the length of time it may take the beach to recover to its original profile, which is dependent on the occurrence of one or a series of major storms; (b) the aesthetic impairment of the beach for a long time, with particular delays in the return of the natural arrangement of log accumulations; and (c) exposure of areas behind the original berm to potential erosion, a problem of more concern in developed areas, but one that definitely would affect the usefulness of this technique at many other spills.

In summary, the results of the berm-relocation projects in PWS appear to us to be quite encouraging. However, the details of the differences in the recovery modes of the different beaches point to the usefulness of having detailed data on wave conditions, sediment types, longshore currents, and seasonal storm patterns at a spill site to properly apply this technique.

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Appendix

Concentrations of
Targeted Polynuclear Aromatic Hydrocarbons
in Samples from Selected Stations
August 1991

LABORATORY ID:	LABORATORY ID:	N1260-15	N1260-12	N1260-05
SAMPLE NAME:	SAMPLE NAME:	N1/2B	N3/1B	N3/3B
Concentration (µg/g)	Concentration (µg/g)			
COMPOUND	COMPOUND			
NAPHTHALENE,a, e	NAPHTHALENE,a, e	N/D**	0.01	N/D**
C-1 NAPHTHALENE	C-1 NAPHTHALENE	N/D**	0.03	0.82
C-2 NAPHTHALENE	C-2 NAPHTHALENE	N/D**	0.21	27.46
C-3 NAPHTHALENE	C-3 NAPHTHALENE	N/D**	0.56	39.15
C-4 NAPHTHALENE	C-4 NAPHTHALENE	N/D**	3.08	41.49
FLUORENE, a, e	FLUORENE, a, e	N/D**	0.04	1.38
C-1 FLUORENE	C-1 FLUORENE	N/D**	0.47	11.34
C-2 FLUORENE	C-2 FLUORENE	N/D**	1.48	25.91
C-3 FLUORENE	C-3 FLUORENE	N/D**	5.09	32.39
DIBENZOTHIO., b, f	DIBENZOTHIO., b, f	N/D**	0.30	9.83
C-1 DIBENZOTHIO.	C-1 DIBENZOTHIO.	0.06	0.88	69.32
C-2 DIBENZOTHIO.	C-2 DIBENZOTHIO.	0.21	14.31	116.07
C-3 DIBENZOTHIO.	C-3 DIBENZOTHIO.	0.45	28.28	116.07
PHENANTHRENE, b, f	PHENANTHRENE, b, f	N/D**	0.15	16.35
C-1 PHENANTHRENE	C-1 PHENANTHRENE	0.03	1.79	98.10
C-2 PHENANTHRENE	C-2 PHENANTHRENE	0.31	8.15	135.27
C-3 PHENANTHRENE	C-3 PHENANTHRENE	0.31	15.81	98.10
ANTHRACENE, b, f	ANTHRACENE, b, f	N/D**	N/D**	N/D**
NAPHTHOBENZTHIO.,b	NAPHTHOBENZTHIO.,b	N/D**	0.71	2.58
C-1 NBTP	C-1 NBTP	N/D**	4.06	7.42
C-2 NBTP	C-2 NBTP	0.28	8.13	9.67
C-3 NBTP	C-3 NBTP	0.70	9.19	10.48
FLUORANTHENE, c, f	FLUORANTHENE, c, f	0.03	0.24	1.75
PYRENE, c, f	PYRENE, c, f	0.04	0.82	2.19
C-1 PYRENE	C-1 PYRENE	0.10	3.12	8.52
C-2 PYRENE	C-2 PYRENE	0.30	3.24	6.34
BENZO(a)ANT.	BENZO(a)ANT.	0.02	N/D**	0.10
CHRYSENE, c, g	CHRYSENE, c, g	0.10	0.90	1.44
C-1 CHRYSENE	C-1 CHRYSENE	N/D**	1.70	2.78
C-2 CHRYSENE	C-2 CHRYSENE	N/D**	2.83	2.58
BENZO(b)FLU.*, d, g	BENZO(b)FLU.*, d, g	N/D**	0.09	0.12
BENZO(e)PYRENE, d, g	BENZO(e)PYRENE, d, g	N/D**	0.24	0.29
BENZO(a)PYRENE, d, g	BENZO(a)PYRENE, d, g	N/D**	0.03	0.05
PERYLENE, d, g	PERYLENE, d, g	N/D**	N/D**	0.06
IND.(1,2,3-cd)PYR., d, g	IND.(1,2,3-cd)PYR., d, g	N/D**	N/D**	N/D**
DIBENZ.(a,h)ANT., d, g	DIBENZ.(a,h)ANT., d, g	N/D**	N/D**	N/D**
BENZ.(g,h,i)PER., d,g	BENZ.(g,h,i)PER., d,g	N/D**	0.15	0.14
TOTAL TARGET AH:	TOTAL TARGET AH:	2.95	116.08	895.56
* b and k isomers comb	* b and k isomers comb	Values valid to two significant figures only.		
** Below detection limit	** Below detection limit			

LABORATORY ID:	N1260-18	N1260-04	N1260-21	N1260-06
SAMPLE NAME:	N5/1A	N6/1B	N7/1B	N7/3B
Concentration (µg/g)				
COMPOUND				
NAPHTHALENE,a, e	N/D**	N/D**	N/D**	N/D**
C-1 NAPHTHALENE	N/D**	N/D**	N/D**	N/D**
C-2 NAPHTHALENE	2.80	1.08	N/D**	N/D**
C-3 NAPHTHALENE	9.10	4.83	N/D**	N/D**
C-4 NAPHTHALENE	35.63	11.32	1.83	2.11
FLUORENE, a, e	0.27	0.13	N/D**	N/D**
C-1 FLUORENE	8.40	1.66	N/D**	N/D**
C-2 FLUORENE	30.46	7.84	0.93	0.58
C-3 FLUORENE	47.27	16.83	4.11	5.64
DIBENZOTHIO., b, f	2.89	0.29	N/D**	N/D**
C-1 DIBENZOTHIO.	63.97	3.67	0.50	0.41
C-2 DIBENZOTHIO.	158.90	14.94	13.72	14.29
C-3 DIBENZOTHIO.	169.22	23.08	34.29	33.13
PHENANTHRENE, b, f	5.52	0.31	N/D**	N/D**
C-1 PHENANTHRENE	78.02	4.26	N/D**	N/D**
C-2 PHENANTHRENE	157.93	12.52	6.74	5.54
C-3 PHENANTHRENE	117.97	21.28	22.13	22.91
ANTHRACENE, b, f	N/D**	N/D**	N/D**	N/D**
NAPHTHOBENZTHIO.,b	4.33	1.90	0.98	0.99
C-1 NBTP	16.51	8.28	4.69	4.97
C-2 NBTP	22.70	10.86	7.43	7.66
C-3 NBTP	24.76	7.20	8.11	10.35
FLUORANTHENE, c, f	2.29	0.22	0.26	0.17
PYRENE, c, f	3.01	0.62	0.85	0.84
C-1 PYRENE	10.32	3.61	2.86	3.62
C-2 PYRENE	8.46	5.51	3.48	2.89
BENZO(a)ANT.	0.10	N/D**	N/D**	0.05
CHRYSENE, c, g	3.25	2.13	1.02	0.98
C-1 CHRYSENE	5.68	2.73	1.82	2.05
C-2 CHRYSENE	7.03	2.73	2.04	1.64
BENZO(b)FLU.*, d, g	0.34	0.59	N/D**	N/D**
BENZO(e)PYRENE, d, g	0.56	0.83	N/D**	N/D**
BENZO(a)PYRENE, d, g	0.05	N/D**	N/D**	N/D**
PERYLENE, d, g	0.09	N/D**	N/D**	N/D**
IND.(1,2,3-cd)PYR., d, g	N/D**	N/D**	N/D**	N/D**
DIBENZ.(a,h)ANT., d, g	N/D**	N/D**	N/D**	N/D**
BENZ.(g,h,i)PER., d,g	0.31	N/D**	N/D**	0.14
TOTAL TARGET AH:	998.17	171.26	117.81	120.97
* b and k isomers comb				
** Below detection limit				

LABORATORY ID:	N1310-03	N1310-05	N1260-11	N1260-14
SAMPLE NAME:	N11/3B	N12/1A	N13/1B	N15/2B
Concentration (µg/g)				
COMPOUND				
NAPHTHALENE,a, e	N/D**	N/D**	N/D**	N/D**
C-1 NAPHTHALENE	N/D**	N/D**	N/D**	N/D**
C-2 NAPHTHALENE	N/D**	0.75	0.28	N/D**
C-3 NAPHTHALENE	N/D**	4.93	1.31	N/D**
C-4 NAPHTHALENE	N/D**	11.64	3.69	0.16
FLUORENE, a, e	N/D**	0.14	N/D**	N/D**
C-1 FLUORENE	N/D**	3.32	0.51	N/D**
C-2 FLUORENE	N/D**	12.33	2.09	0.23
C-3 FLUORENE	0.42	24.67	2.77	0.54
DIBENZOTHIO., b, f	N/D**	28.97	0.09	N/D**
C-1 DIBENZOTHIO.	N/D**	33.42	1.46	N/D**
C-2 DIBENZOTHIO.	0.68	122.55	4.67	0.35
C-3 DIBENZOTHIO.	1.59	118.09	5.60	0.76
PHENANTHRENE, b, f	N/D**	4.11	N/D**	N/D**
C-1 PHENANTHRENE	0.10	41.09	1.58	0.04
C-2 PHENANTHRENE	0.60	108.89	5.02	0.31
C-3 PHENANTHRENE	1.08	86.29	6.46	0.61
ANTHRACENE, b, f	N/D**	N/D**	N/D**	N/D**
NAPHTHOBENZTHIO.,b	0.05	3.34	0.73	0.08
C-1 NBTP	0.32	11.59	2.96	0.49
C-2 NBTP	0.77	16.27	3.58	1.20
C-3 NBTP	0.86	15.60	2.80	1.30
FLUORANTHENE, c, f	0.02	1.54	0.07	N/D**
PYRENE, c, f	0.06	2.47	0.18	0.06
C-1 PYRENE	0.16	8.49	0.92	0.32
C-2 PYRENE	0.18	6.95	1.72	0.61
BENZO(a)ANT.	N/D**	0.07	0.05	0.02
CHRYSENE, c, g	0.08	2.33	0.56	0.28
C-1 CHRYSENE	0.16	4.08	0.89	0.40
C-2 CHRYSENE	0.14	2.91	0.72	0.35
BENZO(b)FLU.*, d, g	N/D**	0.23	0.09	N/D**
BENZO(e)PYRENE, d, g	N/D**	0.43	0.18	N/D**
BENZO(a)PYRENE, d, g	N/D**	0.05	N/D**	N/D**
PERYLENE, d, g	N/D**	0.13	N/D**	N/D**
IND.(1,2,3-cd)PYR., d, g	N/D**	0.06	N/D**	N/D**
DIBENZ.(a,h)ANT., d, g	N/D**	0.11	N/D**	N/D**
BENZ.(g,h,i)PER., d,g	N/D**	0.28	N/D**	N/D**
TOTAL TARGET AH:	7.27	678.13	50.97	8.10
* b and k isomers comb				
** Below detection limit				

LABORATORY ID:	N1310-04	N1260-03	EXX.VALDEZ
SAMPLE NAME:	N17/1B	N18/3B	REF. OIL
Concentration (µg/g)			
COMPOUND			
NAPHTHALENE,a, e	N/D**	N/D**	963.00
C-1 NAPHTHALENE	N/D**	N/D**	2111.20
C-2 NAPHTHALENE	N/D**	N/D**	2703.81
C-3 NAPHTHALENE	N/D**	1.18	2000.08
C-4 NAPHTHALENE	N/D**	3.30	1074.12
FLUORENE, a, e	N/D**	N/D**	118.03
C-1 FLUORENE	N/D**	0.26	266.86
C-2 FLUORENE	N/D**	2.84	405.42
C-3 FLUORENE	0.05	5.22	390.02
DIBENZOTHIO., b, f	N/D**	N/D**	337.61
C-1 DIBENZOTHIO.	0.06	N/D**	554.29
C-2 DIBENZOTHIO.	0.45	6.61	705.46
C-3 DIBENZOTHIO.	0.86	10.54	604.68
PHENANTHRENE, b, f	N/D**	N/D**	394.94
C-1 PHENANTHRENE	0.08	0.18	836.35
C-2 PHENANTHRENE	0.42	5.72	929.27
C-3 PHENANTHRENE	0.78	12.01	789.88
ANTHRACENE, b, f	N/D**	N/D**	5.11
NAPHTHOBENZTHIO.,b	0.04	1.51	55.43
C-1 NBTP	0.19	6.61	201.56
C-2 NBTP	0.43	7.65	292.26
C-3 NBTP	0.81	4.75	267.07
FLUORANTHENE, c, f	0.02	0.57	22.45
PYRENE, c, f	0.03	1.61	30.87
C-1 PYRENE	0.16	10.28	182.39
C-2 PYRENE	0.25	16.88	259.55
BENZO(a)ANT.	0.01	N/D**	N/D**
CHRYSENE, c, g	0.05	6.92	92.65
C-1 CHRYSENE	0.11	11.08	165.45
C-2 CHRYSENE	0.08	9.69	191.92
BENZO(b)FLU.*, d, g	N/D**	N/D**	100.90
BENZO(e)PYRENE, d, g	N/D**	N/D**	23.19
BENZO(a)PYRENE, d, g	N/D**	N/D**	4.00
PERYLENE, d, g	N/D**	N/D**	13.76
IND.(1,2,3-cd)PYR., d, g	N/D**	N/D**	N/D**
DIBENZ.(a,h)ANT., d, g	N/D**	N/D**	N/D**
BENZ.(g,h,i)PER., d,g	N/D**	N/D**	N/D**
TOTAL TARGET AH:	4.87	125.43	17093.58
* b and k isomers comb			
** Below detection limit			

Glossary

AS	asphalt pavement
cm	centimeter
CT	coat
EPA	United States Environmental Protection Agency
FL	film
FOSC	Federal On-Scene Coordinator
GC/MS	gas chromatograph/mass spectrometer
HOR	heavy oil residue
km	kilometer
LOR	light oil residue
LSU	Louisiana State University
MAYSAP	May Shoreline Assessment Program
MOR	medium oil residue
MMS	Mineral Management Service
NCP	National Contingency Plan
NOAA	National Oceanic and Atmospheric Administration
OF	oil film
PAH	polycyclic aromatic hydrocarbon
PWS	Prince William Sound
RPI	Research Planning Inc.
SSC	Scientific Support Coordinator (NOAA)
ST	stain
TAG	Technical Advisory Group
TPH	total petroleum hydrocarbons
USCG	United States Coast Guard

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