GEOMORPHOLOGICAL CONTROLS ON THE PERSISTENCE OF SHORELINE CONTAMINATION FROM THE *EXXON VALDEZ* OIL SPILL

Jacqueline Michel and Miles O. Hayes
Research Planning, Inc.
Post Office Box 328
Columbia, SC 29202

Prepared for

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

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EXECUTIVE SUMMARY

As part of NOAA's scientific support to the U.S. Coast Guard during the EXXON VALDEZ oil spill, a series of shoreline monitoring programs were conducted, starting in September 1989. The primary objective of these programs was to provide the scientific basis for recommendations on shoreline treatment strategies for 1990 and beyond. Much of the information gained from these studies was incorporated into plans developed in early 1990, in which general guidelines for shoreline treatment were formulated and refined, as specific treatment issues arose.

A secondary objective of these studies was to provide a physical/chemical framework for the sites included in NOAA's biological monitoring program. These sites included sections of shoreline that had been set-aside (not treated) for research purposes, so that environmental effects and oil persistence on untreated shorelines could be compared with those shorelines that had received various types of treatment.

This report presents the results of the geomorphological and sedimentological studies, as well as seasonal and on TPH concentrations, which provide a framework for the understanding of the basic physical/chemcial function of the oiled environments. The primary study consisted of ten surveys at 18 permanent sites, and additional surveys at eleven other sites. A brief report on the results of a survey of most of the permanent stations, as well as 9 berm relocation sites, carried out in January 1991 is included as Appendix A.

The major conclusions and recommendations derived from the study of the monitoring stations are grouped below by shoreline type:

Exposed Gravel Beaches

- The gravel beaches of Prince William Sound (PWS), because of the unique combination of being somewhat sheltered and recently uplifted during the 1964 earthquake, present special problems not encountered before at a major spill. Consequently, we were able to distinguish several different modes of response of gravel beaches to oil spills not recognized before.

- We could not detect any difference in the removal rates of surface and subsurface oil in those stations that were heavily treated versus those lightly treated in 1989 on the shorelines we termed <u>cobble/boulder platforms with berms</u>, for which we have six permanent monitoring stations. These types of shorelines are among the most exposed in PWS and all shorelines of this type had 85-95 percent removal of surface oil over the storm season. At future spills on beaches of this type, the benefit of recovering a relatively small amount of oil has to be weighed against biological impacts to the intertidal communities resulting from the treatment itself.

- Subsurface oil persists, and will continue to persist, at the highest concentrations remaining in PWS on gravel beaches where a stable surface armor of cobbles and boulders has evolved. Although they comprise a small part of the oiled shoreline in PWS, these shorelines pose the greatest problem for treatment for 1991 because of the relatively large amount of oil present, the degree of surface disturbance needed to remove the armor, and, particularly, the fact that the oil extends to below the middle intertidal zone, where biological impacts from the cleanup activities would be great. During the 1991 shoreline spring surveys, special care should be taken to identify sections of shoreline where a stable surface armor may be sheltering subsurface oil from natural removal.

- Two additional major physical aspects of cobble/boulder platforms with berms determines their potential for retaining subsurface oil. These are:

  A. Relative exposure to storm waves, with those stations with long, effective fetches open to the east and northeast being cleaned most rapidly.

  B. Thickness of sediment occurring between the surface armor and bedrock, with the thinner sediment veneers being cleaned more rapidly.

- Berm relocation at some sites may have exacerbated the problem of persistent subsurface oil under the armor where the excavated sediments were relocated below the high-tide line and piled on top of the armored surface. These stations need to monitored carefully during the spring surveys.

- The studies carried out in the Outer Kenai Peninsula showed some major difference between gravel beaches there and those in PWS. Penetration of oil under an armored sediment surface on shore platforms was uncommon, but burial of oil layers under accretionary berms on exposed gravel beaches was a common problem. Extensive asphalt pavements developed on some of the more sheltered, downwarped coastlines. In general, cleanup was much simpler on the

Outer Kenai than in PWS, except where oil layers were buried deeply (10's of cm) under gravel berms.

Bayhead Gravel Beaches

- Because of the overall depositional nature of bayhead beaches, they have potential for long-term persistence of subsurface oil.

- From a strict oil-persistence perspective, bayhead beaches benefitted greatly from treatment efforts. With the heavy degree of oiling, permeable sediments, and sporadic wave energy of this shoreline type, there would have been little natural removal, particularly with depth. In 1990, asphalt pavements had already started to form where surface oil deposits had not been completely removed in 1989.

- Berm relocation was only partially effective in removal of subsurface oil in that it targeted removal of oil only from the storm and spring berms. Natural removal of the subsurface oil from the middle part of Sleepy Bay, which had the deepest subsurface oil found in PWS, will be very slow. This shoreline type will continue to pose cleanup issues in 1991.

Sheltered Rocky Shorelines

- Rocky shorelines covered with poorly sorted rubble have the potential for oil to penetrate deeply if the rubble layer is thick (up to 45 cm). This is in contrast to pure bedrock shorelines, where penetration was usually very small, limited by the shallow bedrock surface or the compacted surficial sediments.

- Where heavily oiled, formation of pavements from oil accumulation on the surface of the rubble veneer is likely. Shoreline treatment techniques under these conditions would remove a significant amount of oil that would otherwise persist for long periods in the upper intertidal zone.

In summary, from an oil residence time perspective, the hot-water washing employed in the summer of 1989 was most effective on sheltered rubble slopes and bayhead beaches.

Local geomorphic features, such as crenulate bays and tombolos, had a major influence, both on the original site of impact, and the amount of oil remaining along the impacted shoreline in 1990. Heavily oiled tombolos were among the more conspicuous areas of surface contamination in the spring and summer of 1990, both inside and outside PWS.

Detailed studies of the sediment characteristics of the oiled gravel beaches in PWS revealed an indirect method of predicting residence time of oil on beaches, based simply on sediment texture (sorting and roundness). Stations with sediments showing a high degree of rounding and sorting, such as at Pt. Helen, showed higher rates of removal of both surface and subsurface oil over the storm season of 1989/90 than those with less well-sorted and subangular sediments (e.g., station N-7 on Knight Island).

A combination of lessons learned from the behavior of subsurface oil on the armored platforms and bayhead beaches in PWS, the role played by effective fetch and storm systems in creating different potential hydrodynamic energies (PHE) in PWS, and specific geomorphic and sedimentological controls, has refined our ability to predict the fate and behavior of oil spills on complex, rocky shorelines, both exposed and sheltered.

The EXXON VALDEZ oil spill, more than any other, has stressed the importance of attaining a better understanding of gravel beaches in order to properly treat them at future spills. The results of this study show that gravel beaches exhibit a wide range of morphological and sedimentological behavior, depending upon such variables as local tectonic history, exposure to waves, local sediment sources, and internal character of the local waves. Certain specific problems, such as armoring of wave-cut platforms, were virtually unstudied before this spill, and while we have made some preliminary observations, more quantitative data are needed. Projections of how quickly gravel beaches will recover to normal configurations in response to certain cleanup methods, such as berm relocation and gravel washing and replacement, requires the coastal geologist to call upon studies done on rivers and sand beaches for answers. Research, such as sediment transport studies on a variety of natural gravel beaches, seasonal monitoring of changes in gravel beach morphology at both sheltered and exposed localities, and continued long-term studies of the oiled gravel beaches at the EXXON VALDEZ site, should be initiated to alleviate this problem. The results reported below on our studies at the EXXON VALDEZ site, as well as results from the studies by Exxon and its consultants and the State of Alaska, hopefully will provide a foundation for future research on this difficult problem.

ACKNOWLEDGEMENTS

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Many individuals provided their time and expertise to this project. Nicole Hammett of NOAA and Tom Kelly of Exxon helped coordinate field support and logistics. The October 1989-March 1990 data were collected by Walter J. Sexton, James Gibeaut, Robert Lemon, David Hall, Elizabeth Hagenstein, Eric Nigg, and Lewis Sharman. The field assistance of Ken Finkelstein, Jerry Galt, Mark Hodges, David M. Kennedy, Robert Pavia, Debra Peyton, and Debra Simecek-Beatty of NOAA, is gratefully acknowledged. Greg Barats, David Noe, David Serena, Steve Sturm, and Jim Truman of RPI also participated in the field work. We thank NOAA pilot Gary Van Den Berg and numerous ERA pilots for providing safe transit to and from our stations. Lynn Crystal of the NWS office in Valdez provided weather briefings for our field surveys and copies of the surface weather maps for our analysis.

We want to thank the RPI staff who also contributed to the production of the final report. Jeff Dahlin did extensive error-checking, data management, and preparation of most of the computer-generated plots. Joe Holmes was responsible for all figures and photographs used in this report, with the assistance of Becky Cook and Tom Simpson. Dot Zaino processed all the text.

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INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has provided scientific support to the U.S. Coast Guard (USCG) for the EXXON VALDEZ oil spill since 24 March 1989. As the Federal On-Scene Coordinator (FOSC), the USCG has the responsibility for management and oversight of Exxon's spill response and cleanup program. As the summer 1989 cleanup activities were drawing to a close, the FOSC requested that NOAA conduct several programs over the fall and winter which would assist the FOSC in determining appropriate treatment needs and technologies for shoreline cleanup in 1990 and beyond. One of these programs was the monitoring of the physical persistence of oil on the shoreline of Prince William Sound (PWS) over the fall and winter of 1989/90, chemical characterization of the residual oil, and development of a 1990 spring forecast of the degree and distribution of shoreline contamination. The field work for this project was contracted to Applied Technology, Inc., with NOAA and Research Planning, Inc. (RPI) providing managerial support. Louisiana State University conducted the chemical analyses. The last field survey was completed in March 1990. NOAA then contracted RPI to continue and expand the program in the spring and summer of 1990. A separate biological program to monitor in PWS the recovery of intertidal communities was contracted by NOAA to Pentec Environmental, Inc. and ERCE, Inc. A concerted effort was made to overlap the study sites of the biological and physical/chemical studies. The spring and summer studies by RPI, in addition to resurveying all the fall and winter monitoring stations twice, were designed to gain a better understanding of the short- and long-term effectiveness of the different cleanup techniques being employed at the site during the field season of 1990. Field work was expanded to include several critical sites in the Outer Kenai Peninsula area. This report presents the physical/chemical results of the entire project for the period September 1989 to September 1990. A brief report on the results of a field survey conducted in January 1991 is presented in Appendix A.

STUDY OBJECTIVES

NOAA's physical/chemical monitoring program at the EXXON VALDEZ spill site had several important objectives:

1) Determine the persistence of oil at selected stations representative of the various shoreline types, degree of exposure, extent of oiling, and treatment received during the summers of 1989 and 1990;

2) Track storm activity through deployment of meteorological stations in the northern, central, and southern regions of PWS;

3) Monitor the beach morphology changes and correlate them with storm intensity, wind direction, effective fetch, tectonic effects, and sediment type;

4) Quantify the oil changes at the monitoring sites and estimate the amount of oil remaining on the shoreline as of spring and September 1990;

5) Characterize the weathering trends in chemical composition of the residual oil in both surface and subsurface sediments, for determination of treatability requirements and toxicity/bioavailability of oil remaining on the shoreline in 1990; and

6) Provide a physical/chemical baseline for the biological studies.

The focus of the NOAA program was PWS; limited personnel and logistical support prevented the deployment of field teams for monitoring of stations outside PWS. However, enough reconnaissance field work was done in the Outer Kenai area to allow generalizations about the fate of the oil in that more exposed region.

THE SPILL

The release of nearly 11 million gallons of Prudhoe Bay crude oil from the EXXON VALDEZ on 24 March 1989 resulted in the largest spill in U.S. history. This spill was unique in many ways, particularly in the extent and degree of shoreline contamination. The weather during the first three days of the spill was calm, and the slick was very thick and relatively contiguous. Skimmers were actively recovering oil, but they were hampered by insufficient offloading capability. On Sunday afternoon, 26 March, the weather changed, and strong winds (up to 70 knots) blew out of the north. The oil slick was broken up and pushed south into the circulation pattern which flows in Hinchinbrook Entrance, along either side of Knight Island, and out Montague Pass. Most of the oil passed east of Knight Island and straight out Montague Pass, but large slicks also made their way north and west of Knight Island, eventually exiting through one of the multiple passes to the west. The location and degree of shoreline contamination along the oil slick trajectory in PWS was determined by timing of east and west wind events. Northwest-facing embayments in the path of the slicks fared poorly, with some nearly filling up with oil as large slicks were pushed in by north-northeasterly winds. The winds on 26

March also provided the energy needed to form a water-in-oil emulsion which immediately more than doubled the volume of "oil" on the water.

Galt and Payton (1990) estimate that 20±5 percent of the oil exited PWS and passed along the Kenai Peninsula, into parts of Lower Cook Inlet. They estimate that about 1 percent reached Shelikof Strait and Kodiak Island. The slicks moving along the Kenai/Kodiak regions were very different from the initial oil in PWS. Weathering and transport processes had created broken streamers and tarballs. Instead of thick oil blanketing kilometers (km) of shoreline, the oil stranded in patches, with heavy oil remaining in some sheltered bays.

The initial response focussed on skimming of oil from the water, while there were still recoverable amounts of oil present. Shoreline cleanup efforts geared up more slowly, as extensive logistics were set in place to support a totally water-based operation. Shoreline cleanup began in early May, peaking in July with over 11,000 people involved. All year 1 shoreline work terminated by 15 September 1989.

FATE OF THE OIL

There has never been an oil spill that contaminated more shoreline than the EXXON VALDEZ. Massive efforts were needed just to survey the oiled shoreline and document the extent and degree of contamination. To date, three such efforts have been made and the results are shown in Table 1:

1) Initial Oiling - As mapped by Shoreline Cleanup Assessment Teams (SCAT), starting in April 1989 and ending in August 1989. SCAT teams were contracted by Exxon and consisted of a geomorphologist, biologist, and archaeologist. They produced field sketches showing the oil distribution along "segments" of variable length that had some inherent similarity in the shoreline morphology and oiling. The data in Table 1 was obtained from the CAMEO VALDEZ database on shoreline mileages for each category as of 26 September 1989.

2) Fall 1989 - Both Exxon and ADEC conducted September/October surveys of PWS, with Exxon using extensive videotaping and ADEC conducting a "walk-a-thon". The data in Table 1 are for the ADEC survey.

3) Spring 1990 - Spring Shoreline Assessment Teams (SSAT) surveyed the impacted area in March and April 1990. The SSAT teams consisted of

representatives from Exxon, State and Federal agencies, and land owners who were encouraged to make comments about the data collected by the Exxon contract geologists and biologists. Surveys were conducted by boat and on foot. The objective of these surveys was to generate detailed work orders for the 1990 cleanup for each segment. Because of the need for more detailed delineation of the shoreline, segments were divided into sub-divisions.

The definitions for the various classes of oiling varied somewhat between surveys, but not significantly so. The data in Table 1 are probably the most accurate and detailed known for any spill. Some trends are:

1) When transported along shore (rather than offshore or directly onshore), large oil spills can contaminate very large sections of shoreline.

2) Natural removal of oil along the more exposed Kenai and Kodiak shorelines was much more effective than in PWS. The percent of moderate-to-heavy oiling remaining in PWS as of spring 1990 was double that elsewhere.

3) Removal rates are logarithmic, that is, the rates slow significantly over time.

4) The largest reduction in oiled length was for the very lightly oiled shorelines in the Kodiak/Shelikof region.

The oiled shoreline remaining as of spring 1990 represents the problem areas where oil has persisted after a year of intensive shoreline treatment and storm activity. These areas probably will be the focus of attention in 1991 and beyond, the critical issue being how intensive are we willing to allow cleanup to extend in order to remove this residual oil.

TABLE 1. Summary of the distribution of oil on the shoreline from the EXXON VALDEZ oil spill over time. Numbers are miles of oiled shoreline.

	Initial Oiling	Fall 1989	Spring 1990
PWS			
Heavy	209.5	44.9	12.9
Moderate	163.4	39.8	28.6
Light	270.2	81.2	49.7
Very Light	146.5	194.2	169.8
Total	**789.6**	**360.1**	**261.0**
Kenai/Cook Inlet			
Heavy	49.4	6.0	1.6
Moderate	73.0	8.0	4.8
Light	157.4	15.0	9.9
Very Light	232.8	52.0	53.4
Total	**512.5**	**161.0**	**69.7**
Kodiak/Shelikof			
Heavy	16.4	0.3	0.4
Moderate	55.6	1.0	3.2
Light	201.8	5.0	4.3
Very Light	1,669.1	41.0	59.1
Total	**1,942.7**	**47.3**	**67.0**
Spill Total	**3,244.8**	**568.4**	**397.7**

SUMMARY OF SHORELINE TREATMENT TECHNIQUES

Early in the spill, it was very apparent that, in order to remove the oil from the shoreline, very intensive techniques would be needed. The 1989 cleanup activities in PWS centered on cold-to-hot water washing of the shoreline, with the objective to remove as much of the oil as possible so it would not continue to refloat and oil other areas and organisms, i.e., be "environmentally stable". Three types of washing equipment were developed:

1) Landing Craft Vessel (LCV) System - Small (40-foot) LCVs were equipped to produce high volumes of cold water, localized high-pressure warm water, and 250 gpm of 140°F water. Hoses were laid ashore, with individual workers holding hoses and directing warm and hot water to liquify the oil and water to wash it to the water surface for recovery by skimmers or sorbent booms.

2) Maxibarge System - A larger, barge-based system capable of producing high volumes of hot and cold water. Much of the equipment was containerized. It had a manlift from where workers could spray the shoreline. It also had the capability of spraying the shoreline directly from the barge deck with fire monitors.

3) Omniboom System - A barge with high capacity pumps to deliver hot water via a telescoping boom and 8-nozzle articulating spray head. This system could deliver 500 gallons per minute of 140°F water through the spray head with a minimum number of workers onshore. Booms were still used to contain the mobilized oil for skimming or sorption into pom-pom booms. The omniboom was used mostly on rocky shores and other areas which were inaccessible to ground crews and small boats. It was seldom used on gravel beaches because the intertidal zone was too wide.

The only other technique used widely in PWS was bioremediation via nutrient addition. At the very end of the 1989 cleanup period, approval was granted for widespread application of two types of fertilizers: Inipol EAP22, a liquid oleophilic fertilizer designed to adhere to oil, consists of a saturated solution of urea in water contained in an oleic acid microemulsion; and Customblen, a slow release formulation of soluble nutrients encased in a polymerized vegetable oil. Inipol application in 1989 was restricted to "beaches", that is, shorelines composed of gravel rather than steep rocky shores. About 120 km of shoreline in PWS were treated with Inipol in August and September 1989.

Shoreline treatment techniques were changed dramatically in 1990. Hot-water washing was limited to a few small areas, with small Landa units being used for "spot washing". For most of the summer, manual removal of oiled debris, heavily oiled surface sediments, and asphalt pavements was conducted by small work crews. About mid-summer, tracked vehicles were tested for use in sediment tilling and opening up heavily oiled storm and spring-tide berms. By the end of 1990, "berm relocations" had been completed at 30 sites. This technique involved excavation by mechanized equipment of much of the sediments in the high-level berms and transport of it to the upper- and mid-tide zone. The objective was to allow tidal flushing, aided by wave action, to release the oil and use sorbent booms to recover the released oil. The sediments were to be left strewn on the shoreline to allow reworking of the sediments and further removal of the oil by storm waves. Thus, only segments exposed to storm waves were treated in this manner.

Inipol and Customblen application was an integral component of all the 1990 treatment techniques. In fact, the underlying philosophy expressed to us by a prominent member of the TAG committee was that the manual removal and berm relocation efforts were primarily pre-treatment efforts to enhance the effectiveness of bioremediation. All shoreline treatment included the application of Inipol and/or Customblen. Customblen was reapplied on a 15-day interval, with Inipol being reapplied every 30 days.

FIELD SURVEY TEAMS

This report is a synthesis of data collected by numerous people on various teams. The initial 18 NOAA stations were established in September 1989 by two teams: 1) Jerry A. Galt (team leader) and Mark Hodges of NOAA, and James Truman of RPI; and 2) Jacqueline Michel (team leader) and Steve Sturm of RPI, and Debra Simecek-Beatty of NOAA.

The surveys conducted from October 1989 to March 1990 were conducted by two teams provided by Advanced Technology, Inc. Team leaders were Walter J. Sexton and James C. Gibeaut. Team members included Elizabeth Hagenstein, David Hall, Robert Lemon, Eric Nigg, and Lewis Sharman. Jacqueline Michel joined these two teams in October and December 1989. The fall and winter surveys were carried out under sometimes trying physical conditions. Heavy snows, cold and icy beaches made it difficult to collect accurate measurements.

The spring 1990 survey were conducted by Jacqueline Michel, Miles O. Hayes, and David Noe of RPI, with the assistance of Debra Simecek-Beatty in May and June 1990. The fall surveys were conducted in September 1990 by two teams led by Ken Finkelstein of NOAA and Jacqueline Michel. Team members were David M. Kennedy, Debra Peyton, Robert Pavia, and Debra Simecek-Beatty of NOAA and Greg Barats and David Serena of RPI.

The logistics for transporting field teams to and from the stations were provided by Exxon for most of the work, with NOAA providing helicopter support in September 1989.

PHYSICAL SETTING OF SPILL SITE

INTRODUCTION

The south-central coast of Alaska is an exceptionally dynamic area with respect to physical processes. Intense tectonic activity, strong winds, large waves, strong tidal currents, and active glaciation interact to produce one of the most rugged and variable coastlines in the world. The Chugach, Kenai, and St. Elias Mountains, an extension of the Cordilleran Mountain system, control the general orientation of the coastline. Rapid advance and retreat of the numerous glaciers that extend down from the mountains have caused sudden and dramatic shifts in loci of erosion and deposition along the coastline.

The oil spilled from the EXXON VALDEZ carried for over 600 km in straight line distance, touching upon four general physiographic regions: (1) Prince William Sound; (2) Outer Kenai Peninsula; (3) Lower Cook Inlet; and (4) the Kodiak/Shelikof Strait area (Fig. 1). PWS was both the most heavily oiled (Table 1) and the most sheltered from wave and storm action of any of the regions. Much of the coastline of the Outer Kenai Peninsula, the second most heavily oiled area, is exposed to some of the largest waves in the world, but it does contain a number of sheltered, drowned glaciated valleys. The Lower Cook Inlet and Shelikof Strait areas have similar geological and energy-level settings. They are both somewhat sheltered from wave action, though not as much as PWS, and both contain a number of large embayments with extensive tidal flats. The southeast side of Kodiak Island is

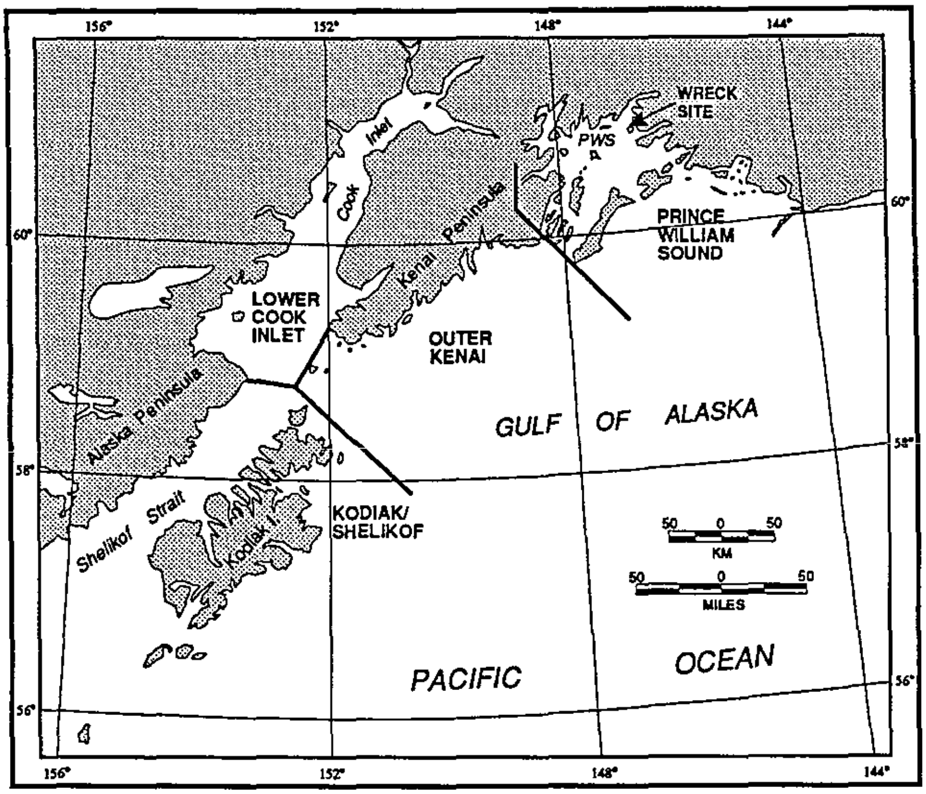


FIGURE 1. Major physiographic regions of south-central Alaska affected by the EXXON VALDEZ oil spill. The bulk of the work for this report was focused on the Prince William Sound (PWS) area.

similar to the Outer Kenai Peninsula, and, of course, the northwest side is on the Shelikof Strait.

TECTONIC SETTING

According to Jacob (1986), the Gulf of Alaska region is one of the most tectonically active regions in the world, with some of the great Alaska earthquakes being the largest recorded on earth. The Pacific Plate under-rides the North American Plate at a relative rate of 5-7 centimeters (cm) per year (Jacob, 1986). A generalized model for present-day crustal deformation in the Gulf of Alaska area is given in Figure 2.

The largest earthquake recorded in the Alaskan-Aleutian area occurred on Good Friday in 1964. It measured 9.2 on the moment-magnitude scale (M_W; Jacob, 1986, p. 152). As seen in Figure 3, the epicenter for this earthquake was at the head of PWS, and most of PWS was subjected to uplift, with over 30 feet (9 m) of uplift recorded on Montague Island. The effects of this uplift are still evident in the area of detailed study for this report, as many places have not regained equilibrium conditions with regard to beach depositional processes. Most of the Outer Kenai, Lower Cook Inlet, and Kodiak/Shelikof areas were subjected to downwarp during the 1964 earthquake. Maximum downwarp on the order of 6 feet (1.8 m) occurred in the Nuka Passage area of the Outer Kenai Peninsula. The effects of the downwarp,

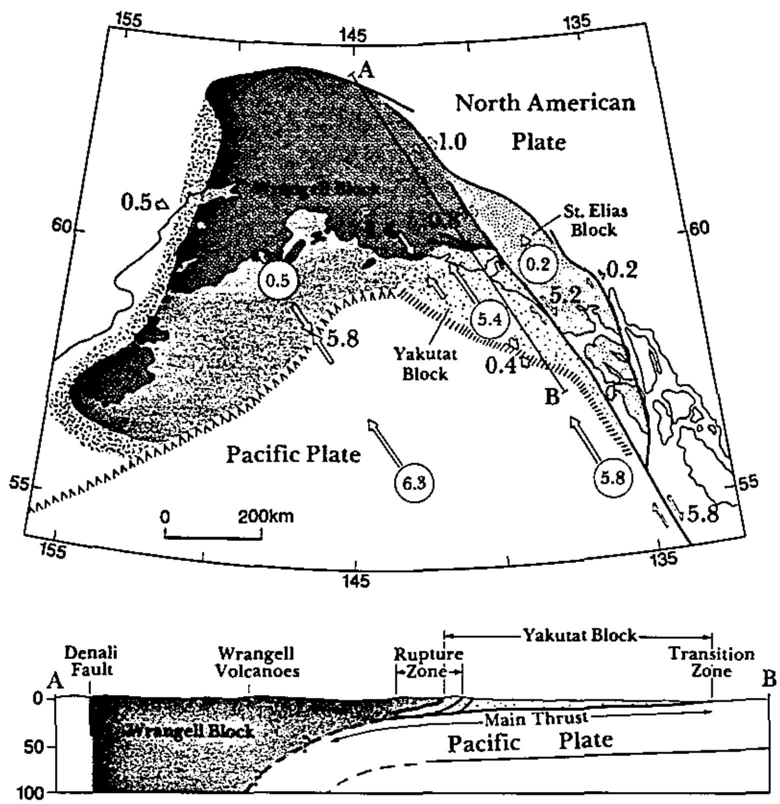


FIGURE 2. Model for present day crustal deformation along the Pacific and North American Plate boundaries (after Lahr and Plafker, 1980; from Jacob, 1986, Fig. 6-8). The circled numbers on the map view are estimates of plate motion in cm/yr of the Pacific Plate, Yakutat Block, and Wrangell Block relative to the North American Plate. Numbers next to the paired vectors represent plate motion across the indicated zones. The rupture zone shown on the A-B cross-section is that of the St. Elias earthquake of 28 February 1979.

such as drowned forests and sunken deltas, are still clearly visible along much of the Outer Kenai coastline.

GEOLOGICAL SETTING

Being located on the leading edge of a major continental plate that is in the process of colliding with an oceanic plate (Fig. 2), the coastline of south-central Alaska has a complex and dynamic geological history. Repeated downwarping and upheavals have led to the formation of complexly intermixed igneous, metamorphic, and sedimentary rocks. It is difficult to generalize about the geology of an area as large as the one affected by the EXXON VALDEZ spill (Fig. 1), consequently, the following remarks are directed toward PWS, the area we focused on during this study.

The geology of PWS includes sedimentary, metasedimentary, volcanic, and granitic rocks (Case et al., 1966). The oldest are the metasedimentary rocks which ring PWS and comprise much of the mainland. These rocks are composed of intermixed layers of slate and sandstone. The thickness of the layers locally determines the size of boulders that form during cliff erosion. The slate can be thin, producing pebble-sized chips as beach sediments.

Most of Knight Island is comprised of volcanic rocks, primarily greenish-black basalts that are referred to as greenstone. The basaltic lava flows are relatively thick, thus the sediments derived from these rocks can be quite coarse. The basalt is also very heavy, with densities of 2.9 gram/cm^3. The density of these rocks is a factor in the size and shape relationships we observed for the clasts on the beaches of PWS.

The remaining islands in PWS and the southeastern tip of Knight Island (from Snug Harbor to Pt. Helen) are composed of slightly metamorphosed sedimentary rocks, mostly sandstones interbedded with platy shales. The rocks are complexly folded, and oftentimes the beds are vertical, such as on Green and Smith Islands. There are localized granites, notably on Perry Island, which produce the light-colored cobbles found on the beaches of that island.

Of note in PWS is the paucity of a source of quartz. Many of the beaches on Knight Island lack a sand-sized component, even with depth. The slates and basalts mechanically break down into granule size [2-4 millimeters (mm)]; below this size, they readily weather to silt and clay particles. Quartz grains are harder than most other minerals in rocks, thus they dominate most sand-sized sediments where there is a source. Furthermore, there are no deep soils because of recent glaciation. Thus, sand-sized sediments are not common along many of the beaches of PWS, with the lack of quartz in the source rocks being one of the causes.

Another notable feature of shoreline sediments in PWS is their coarse size relative to the prevailing wave energy. The bedding plane thicknesses as discussed above are a major factor, but the active tectonic setting is most important. Vertical changes in land elevation during earthquakes are sudden and dramatic. The elevation changes associated with the 1964 earthquake were among the most extensive known to have been related to a single tectonic event. The maximum uplift was 38 feet on Montague Island, though much of the area of concern in our study of the PWS area was uplifted on the order of 4-10 ft. (Plafker, 1971), a significant amount for a region with a mean tidal range of about 10 feet.

The sudden uplift during the Good Friday earthquake, which happened just 26 years ago, has greatly affected most of the shoreline contaminated as a result of the spill, in several ways:

- Introduction of new cliff material to the shoreline by way of landslides. This material is very angular and poorly sorted.
- Removal of beach sediments from the active beach face. These "raised beaches" are readily discernable because they are covered by grasses and alders versus the older tree-covered shoreline.
- Exposure of rocky platforms, formed by waves and/or ice scour, that had been previously submerged.
- Localized changes in the wave and current regime.
- Changes in slopes of intertidal areas.
- Changes in local sediment sources, by changing rock or sediment types exposed to waves and stream courses.
- Changes in nearshore topography that bring about readjustments in wave energy dispersal and refraction.

All of these aspects of change make the prediction of oil burial and dispersal more difficult because such out-of-equilibrium beaches do not exactly follow known patterns of process and response.

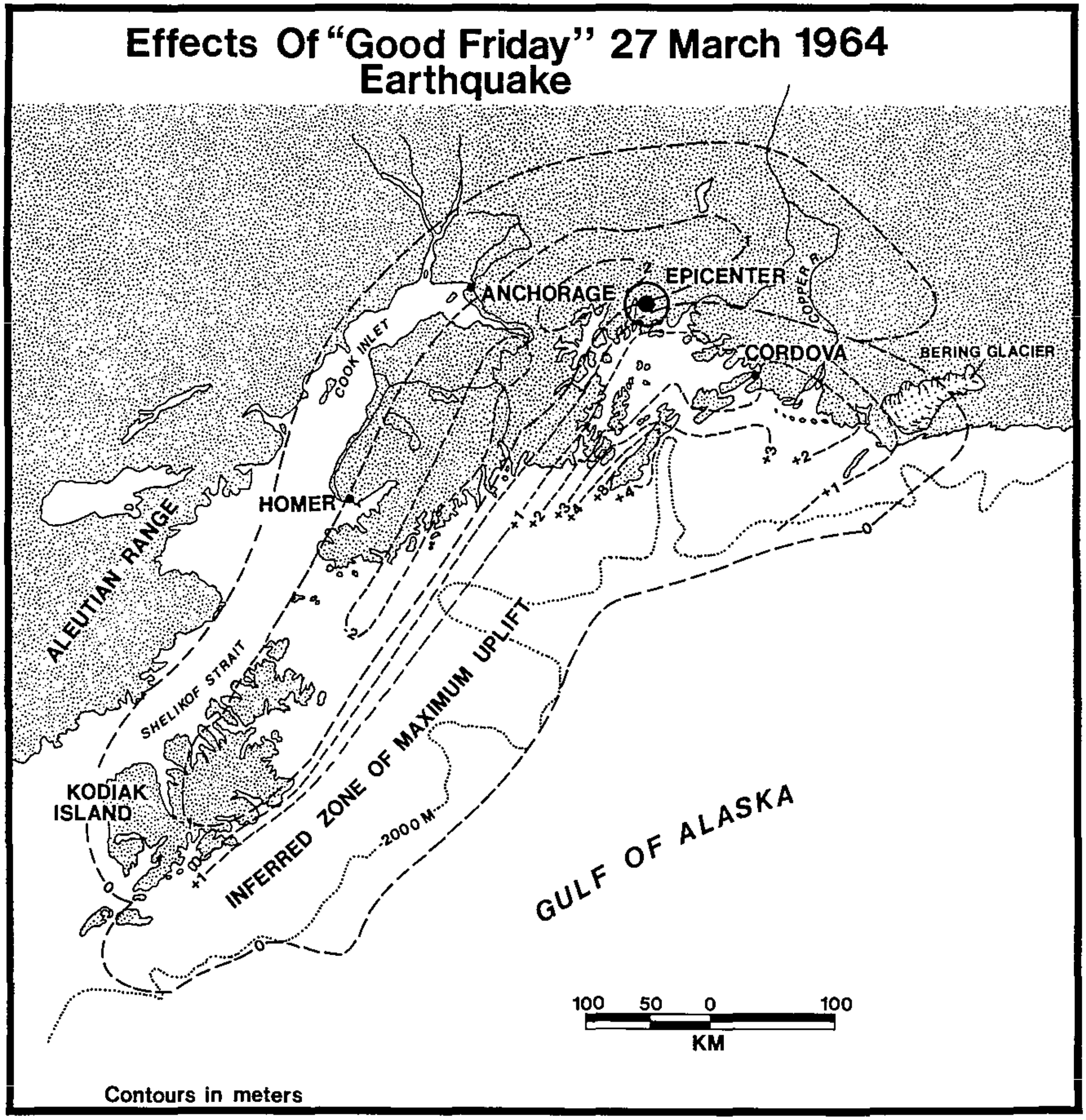


FIGURE 3. Crustal deformations associated with the great Alaskan earthquake of 1964. Note that uplift occurred southeast of the hingeline and that downwarp occurred northwest of it (modified after Plafker, 1969).

CLIMATIC SETTING

General

The presence and positioning of two major persistent fronts, or areas of cyclogenesis, the Pacific Polar and Pacific Arctic fronts, largely govern the wind patterns along the coast of south-central Alaska. The Pacific Polar front, situated off the coast of northern Asia during winter, is the dominant factor. The Pacific Arctic front, which is positioned immediately south of the Aleutians during winter, is responsible for the generation of less intense, localized cyclones.

Cyclonic storms generated along the Pacific Polar front, which have pressure gradients and winds comparable to those of the hurricanes of the southern United States and the Caribbean, tend to travel easterly along the Aleutian Islands into the Gulf of Alaska and stall there. The cyclones are normally prevented from penetrating inland by a steep pressure and temperature gradient caused by a high-pressure system situated over the Alaskan landmass (Nummedal and Stephen, 1976).

This combination of locally-derived Pacific Arctic storms and intense Pacific Polar storms makes the maritime region of the Gulf of Alaska the most frequent cyclogenetic region (during the nonsummer months) in the Northern Hemisphere (Petterssen, 1969, p. 227). During the summer, cyclonic activity decreases markedly, and the storms are of less intensity. The Pacific Arctic front disappears entirely, and many of the Pacific Polar storms are deflected toward the Bering Strait and exert little or no influence on the Gulf (Nummedal and Stephen, 1976). On the outer coast, the winds blow overwhelmingly out the eastern quadrants, generating strong east to west longshore sediment transport. A more detailed discussion of cyclonic activity in the Gulf of Alaska can be found in Nummedal and Stephen (1976) and Wilson and Overland (1986).

A unique aspect of this area is the subpolar climate which allows for the occurrence of alpine and piedmont glaciers in close proximity to the shoreline. These glaciers contribute a considerable amount of sediment to some of the local areas.

Wind and Weather in PWS

Winds in the PWS region are complex, with a wide range of prevailing wind directions, but with storm winds mostly from the southeast-east-northeast. Thus, the east-facing shores of PWS are exposed to the highest winds. Many of these areas also have significant fetch over which waves can be built, so they will be exposed to the greatest wave energy. The mouths of east-facing embayments can be exposed to refracted waves which penetrate some distance into the embayments. Shorelines affected by direct or refracted waves show wave-built features, such as gravel berms.

Three sources of information were used to describe the wind patterns in PWS from September 1989 to March 1990. Data from three meteorological stations established by NOAA were plotted as mean daily wind speeds and wind roses. NOAA's National Weather Service (NWS) office in Valdez provided the daily surface weather maps of the north Pacific since 1 September 1989. Also, the Mariners Weather Log for September 1989 through March 1990 was reviewed. This publication plots the tracks of extratropical cyclone centers at sea level for the north Pacific.

Based on these sources of information and discussion with NWS staff in Alaska, storm activity during the fall and winter of 1989/90 was about normal for that period. Figure 4 shows the tracks of extratropical cyclone centers as plotted in the Mariners Weather Log (National Weather Service, 1990a; b; c). Over the fall and winter, there is a steady buildup of these storms which would affect the wind regime in PWS. September had two storms which quickly passed by; October had three storms which either stalled in the northern Gulf of Alaska (on 17-19 October) or originated there (21-22), or passed closely by (29-30). November had two storm centers pass directly over the Sound in quick succession (3-4, 5-6) and another stall in the Gulf (23-25). In December, three storm centers passed almost directly over the Sound (4-5, 21-24, 29), and another passed to the south (7-9). During January, five storm centers passed close by (6-7, 8-9, 14-15,18-19, 22-23). February, with six storms, had the greatest frequency of storm passages, with four of the storm tracks passing nearly over the same spot in PWS (Fig. 4). These storms passed PWS on February 4-5, 6-7, 14-15, 18-19, 22, and 26-27. By March, there was a significant drop in storm frequency, with only two storms passing over or close to PWS on 3-4, and 14 March.

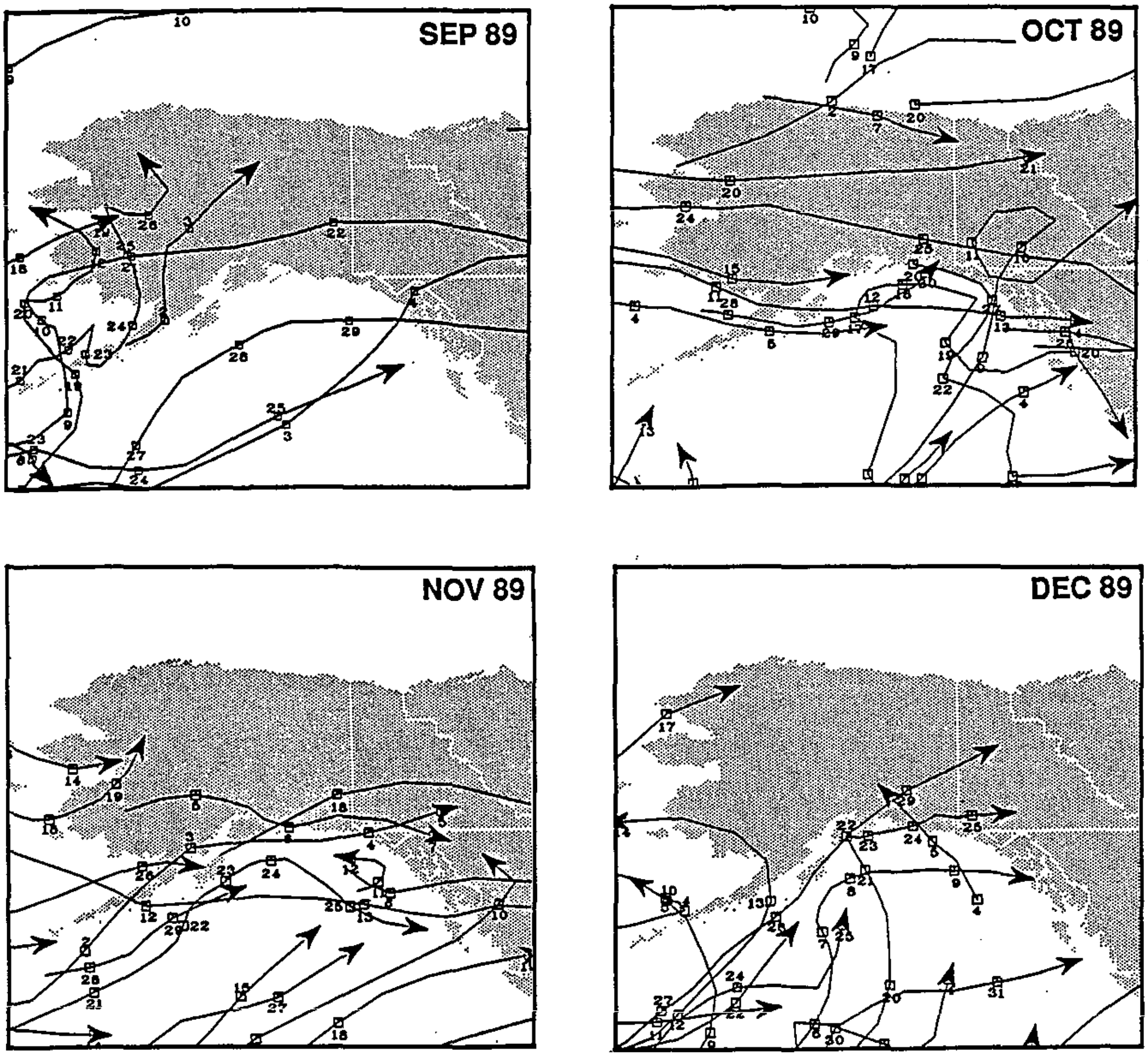
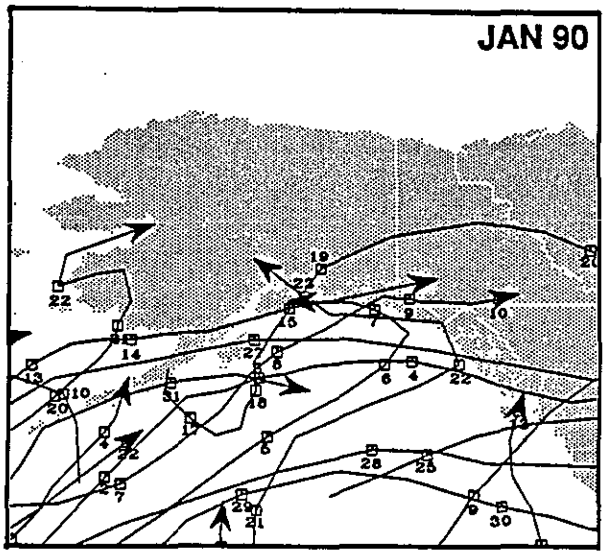


FIGURE 4. Tracks of extratropical cyclones along the coast of south-central Alaska from September 1989 to March 1990 (NWS 1990a; b; c).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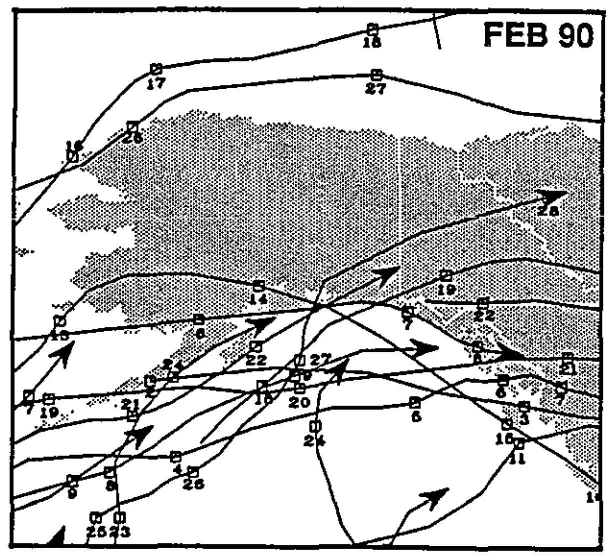
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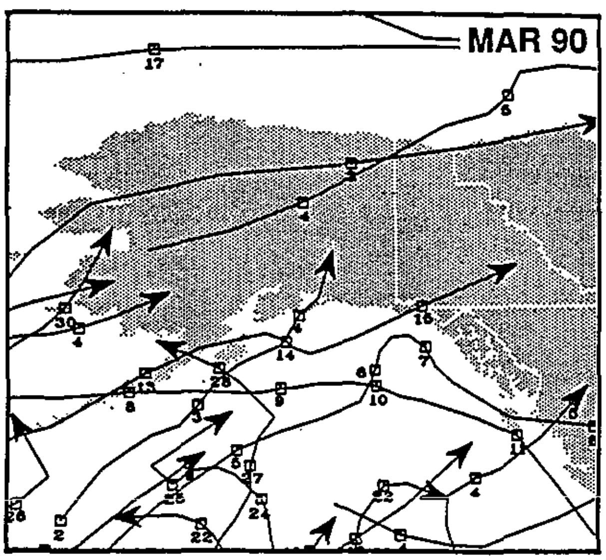
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Study of Figure 4 shows that most of these extratropical cyclones moved east-northeastward, and thus they would generate strongest winds from the southeast, east, and northeast as the storms approached and passed PWS. These storms are usually wet and warm. In 1989/90, they were particularly wet; Valdez set a world record for annual snowfall for a coastal town, with over 1,000 cm of snow.

A second winter weather pattern in PWS is a result of a high pressure forming over the continental landmass of central Alaska. This high pressure system can build up a steep pressure gradient north of PWS, generating very cold, dry winds blowing from the north. These northerly winds are accentuated by the mountain and fjord topography of northern PWS which funnels the winds down natural drainage channels. These northerly "drainage" winds can blow very strongly, as they did three days after the EXXON VALDEZ spill when the slick was widely dispersed by 70 knot winds from the north.

Figures 5 through 7 show the mean daily wind speed for the three stations in PWS at Lonetree, Seal, and Danger Islands (see Fig. 16 for station locations). Wind roses for these stations are shown in Figures 8-10, for all winds and for those greater than 20 miles per hour (mph). There are several important observations that can be made from these figures.

The wind patterns for all three locations are very different, when comparing the daily mean wind speed. PWS has relatively regionalized wind patterns, even when large storms pass through, because of the overriding effects of local topography. For example, Lonetree Island had winds averaging almost 13.5 mph, with definite periods of very high wind activity. There were seven events totalling 25 wind-days with wind speeds averaging over 20 mph for the 100-day period from 22 November 1989 to 6 March 1990 (Fig. 5). For these storm winds, nearly 60 percent of the time winds were from the east and only 30 percent of the time were winds from the north (Fig. 8B). Therefore, even northern PWS is dominated by easterly winds. Of all winds, 50 percent blow in an east-west or west-east pattern (Fig. 8A), reflecting the effects of winds funnelling through Wells Passage to the west. Both Lonetree and Seal Islands are very small, low elevation islands surrounded by open water, without the potential for very localized effects on wind patterns. Thus, these stations provide a good measure of regional wind patterns.

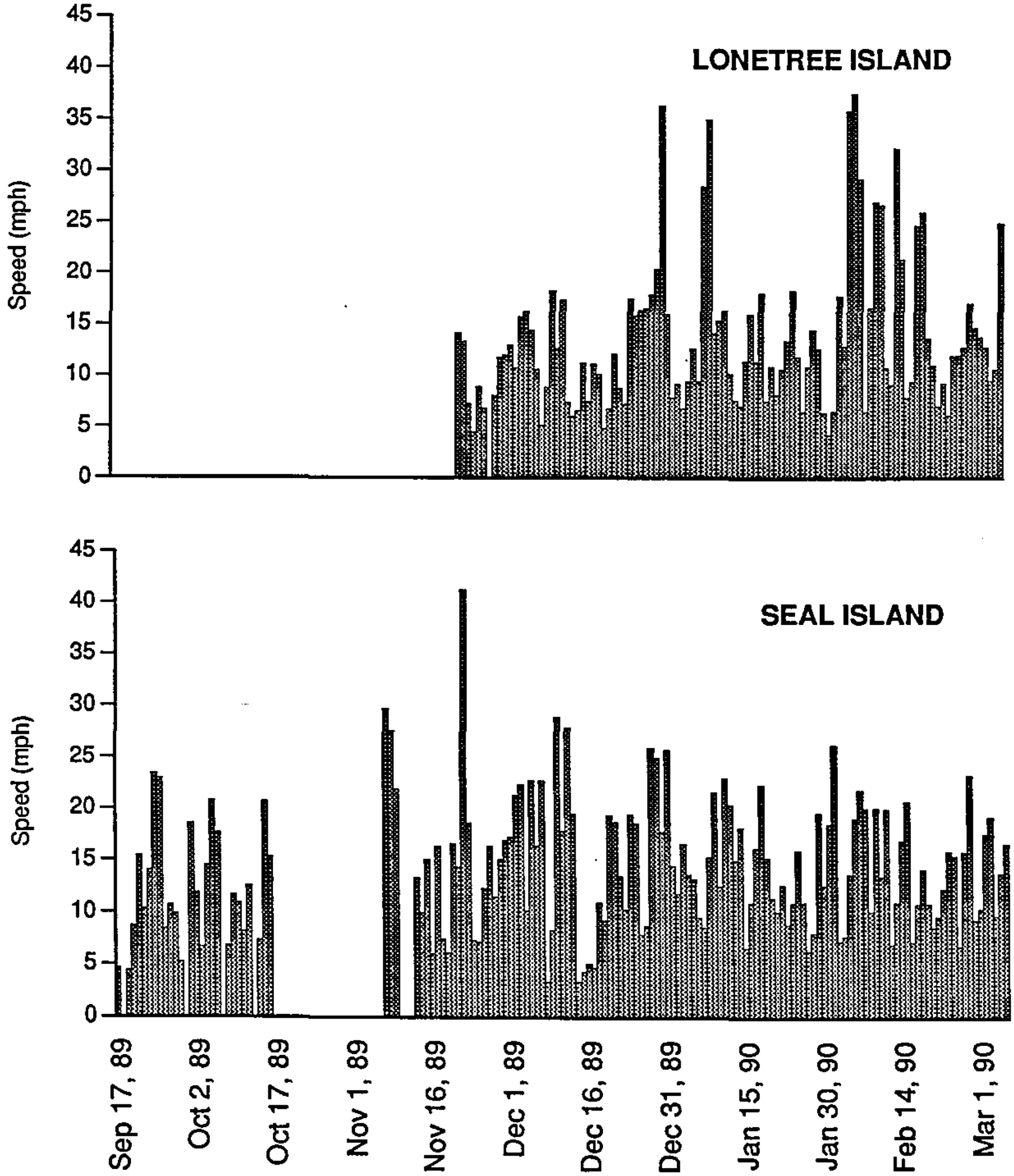


FIGURE 5. (Top) Mean daily wind speeds for the meteorological station on Lonetree Island in northwestern PWS. See Figure 16 for location.

FIGURE 6. (Bottom) Mean daily wind speeds for the meteorological station on Seal Island in central PWS. See Figure 16 for location.

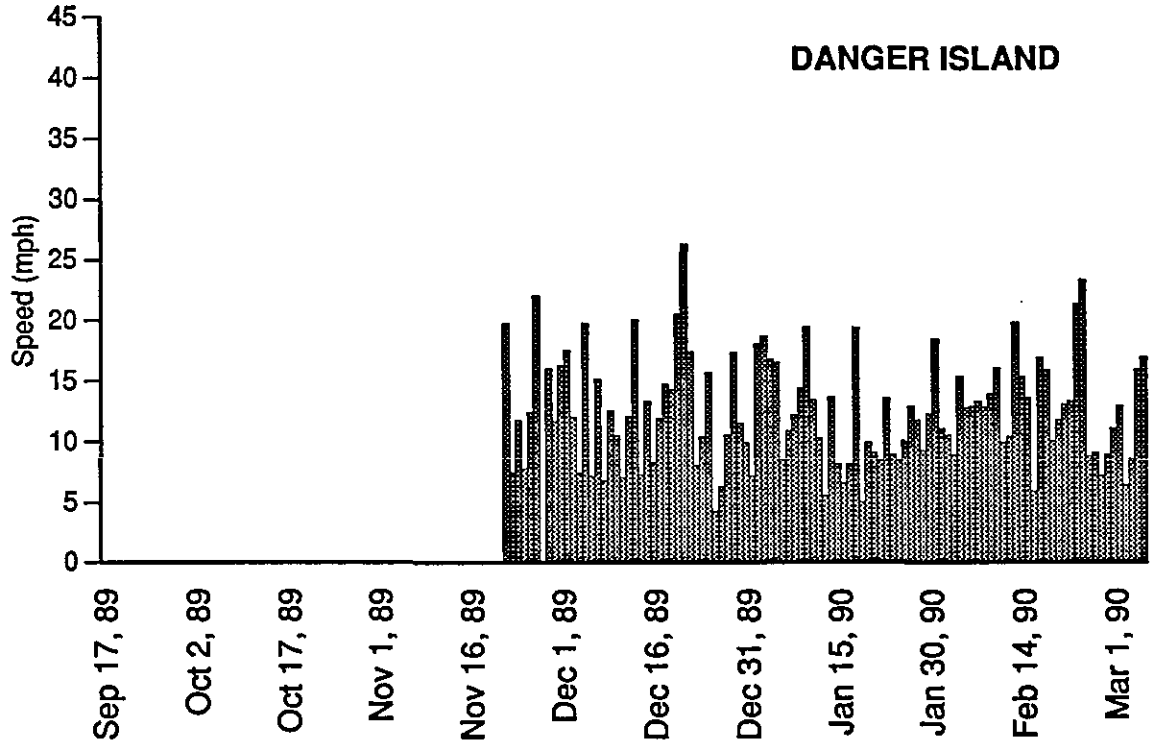
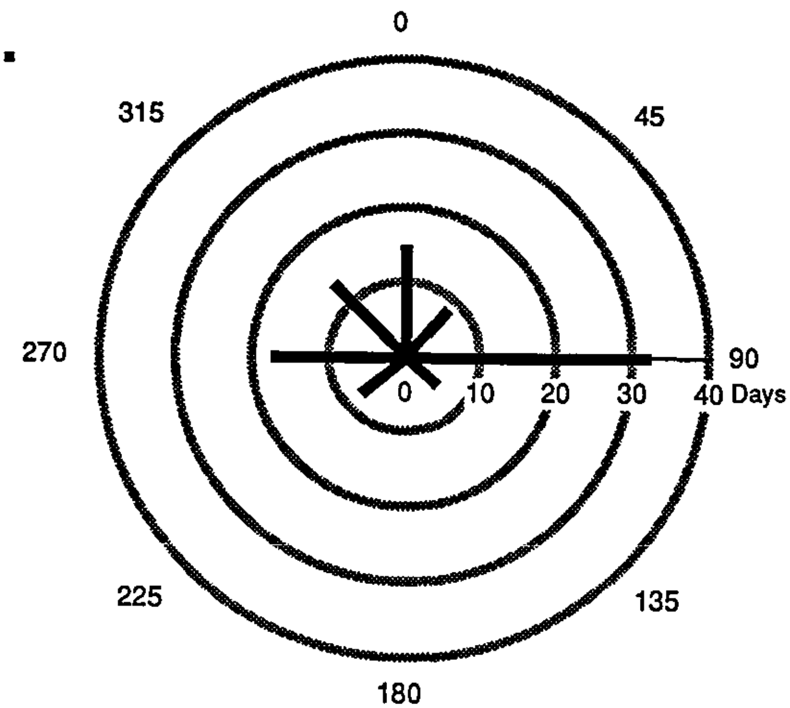


FIGURE 7. Mean daily wind speeds for the meteorological station for Danger Island near the southwestern entrance of PWS. See Figure 16 for station location.

A.



B.

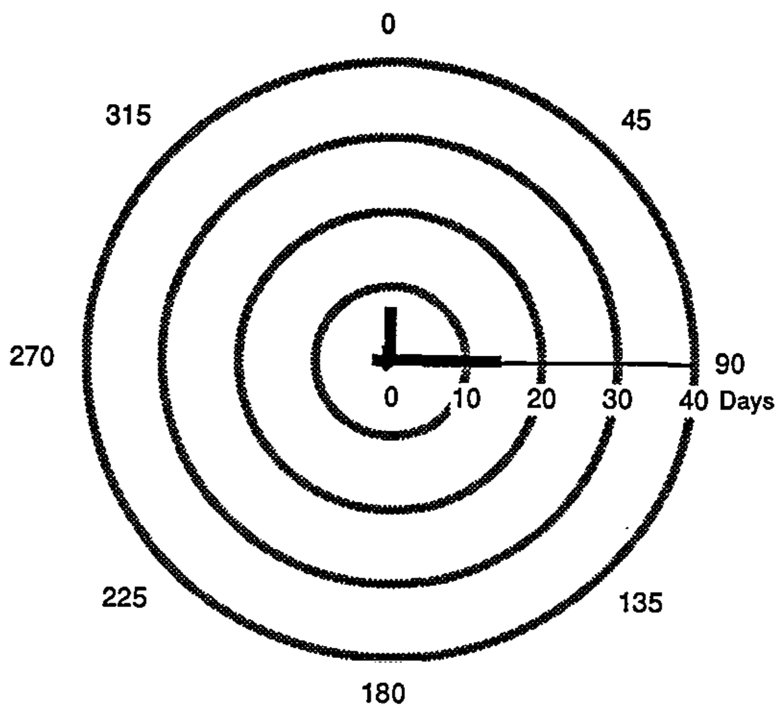
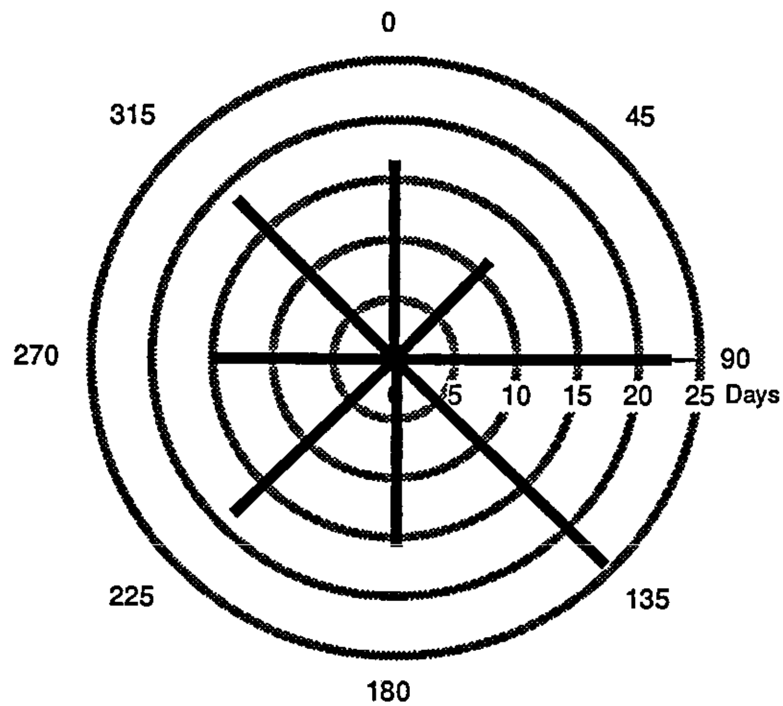


FIGURE 8. Wind roses for the meteorological station on Lonetree Island for the period from 22 November 1989 to 6 March 1990.

A. For all winds.

B. For winds greater than 20 miles per hour.

A.



B.

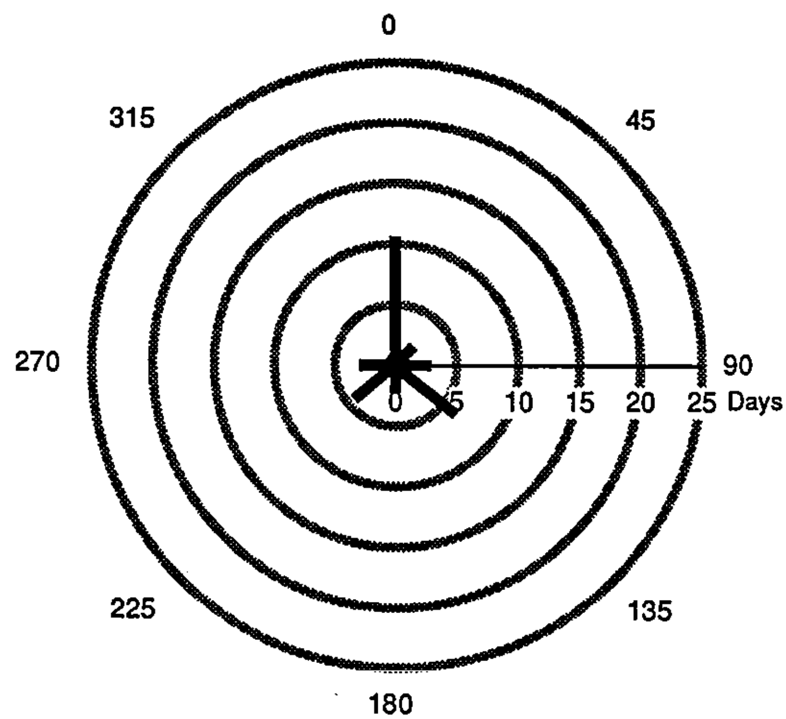
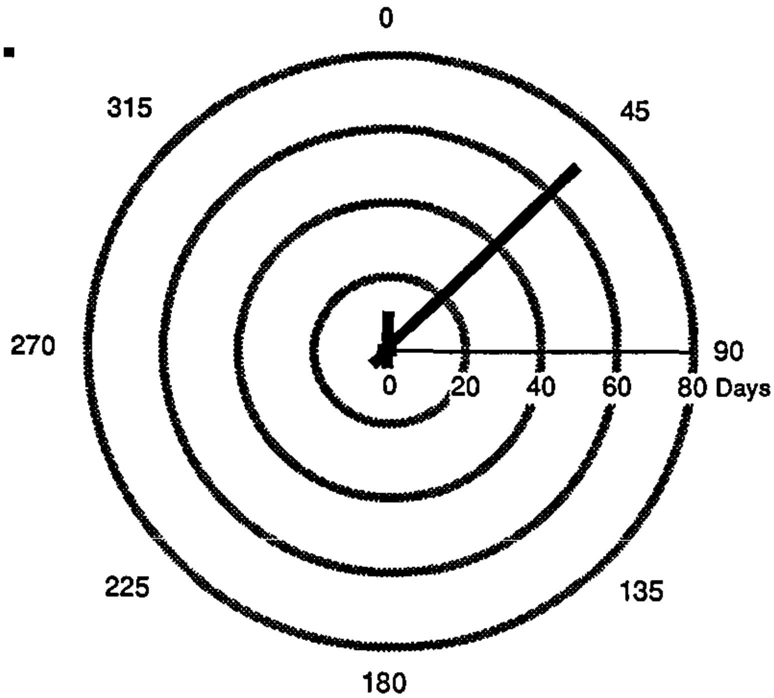


FIGURE 9. Wind roses for the meteorological station on Seal Island for the period from 17 September 1989 to 6 March 1990.

A. For all winds.

B. For winds greater than 20 miles per hour.

A.



B.

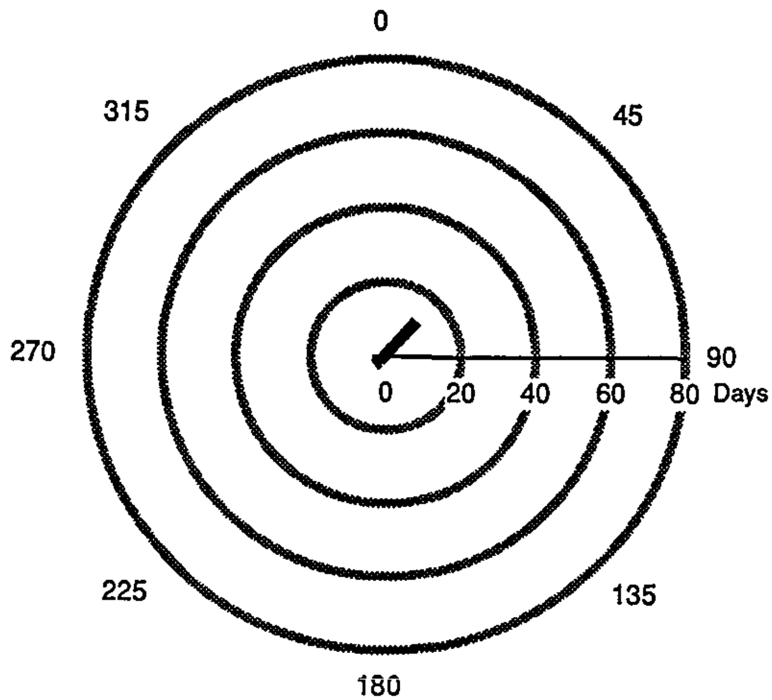


FIGURE 10. Wind roses for the meteorological station on Danger Island for the period from 22 November 1989 to 6 March 1990.

A. For all winds.

B. For winds greater than 20 miles per hour.

Seal Island had at least thirteen events totalling 30 wind-days with daily mean wind speeds greater than 20 mph (Fig. 6) between the period of 17 September 1989 and 6 March 1990. Over 30 percent of these were from the north, and about 40 percent were from the east quadrants. But, the station at Seal Island only had one period of very high wind speeds (daily means greater than 30 mph), compared to the four events at Lonetree, all of which were southeasterly wind events which should have also affected Seal Island. It appears that the high elevations (nearly 1,000 m) on Montague Island partially shelters the station on Seal Island from the very high southeasterly winds generated by extratropical storms passing nearby PWS.

The wind pattern at Danger Island is remarkably different from the stations inside PWS. Over 90 percent of all winds are from the northeast, being channeled down Latouche Passage and Montague Strait. These winds blew fairly steady, with an average speed of 12.5 mph. However, the winds at Danger Island are dominated by channelized winds; they do not even reflect the passage of most storms since only 10 percent of the winds were from any direction other than the northeast. Thus, the station on Danger Island does not reflect general coastal wind patterns further inside PWS.

After review of all the available information, it appears that the period of greatest storm intensity was in February, when four storms generated winds at daily mean speeds greater than 25 mph in the northern part of PWS. These four events were not as strongly manifested in central PWS, as monitored by the meteorological station on Seal Island (Fig. 6).

OCEANOGRAPHIC SETTING

Waves

Actual field observations of wave conditions in the area affected by the EXXON VALDEZ spill are sparse. Nummedal and Stephen (1976) computed deepwater wave-energy flux values for the entire Gulf of Alaska, which can be directly related to longshore transport rates of sediments (Coastal Engineering Research Center, 1973, pp. 4-101). The wave-energy flux for a given sea state is defined as total wave energy per unit area of the sea surface times the velocity of propagation of this energy. The results of their calculations, as well as some inferred longshore sediment transport directions for the Gulf, are given in Figure 11. In the area to the southeast of PWS, resultant wave energy flux is oriented northwest, and

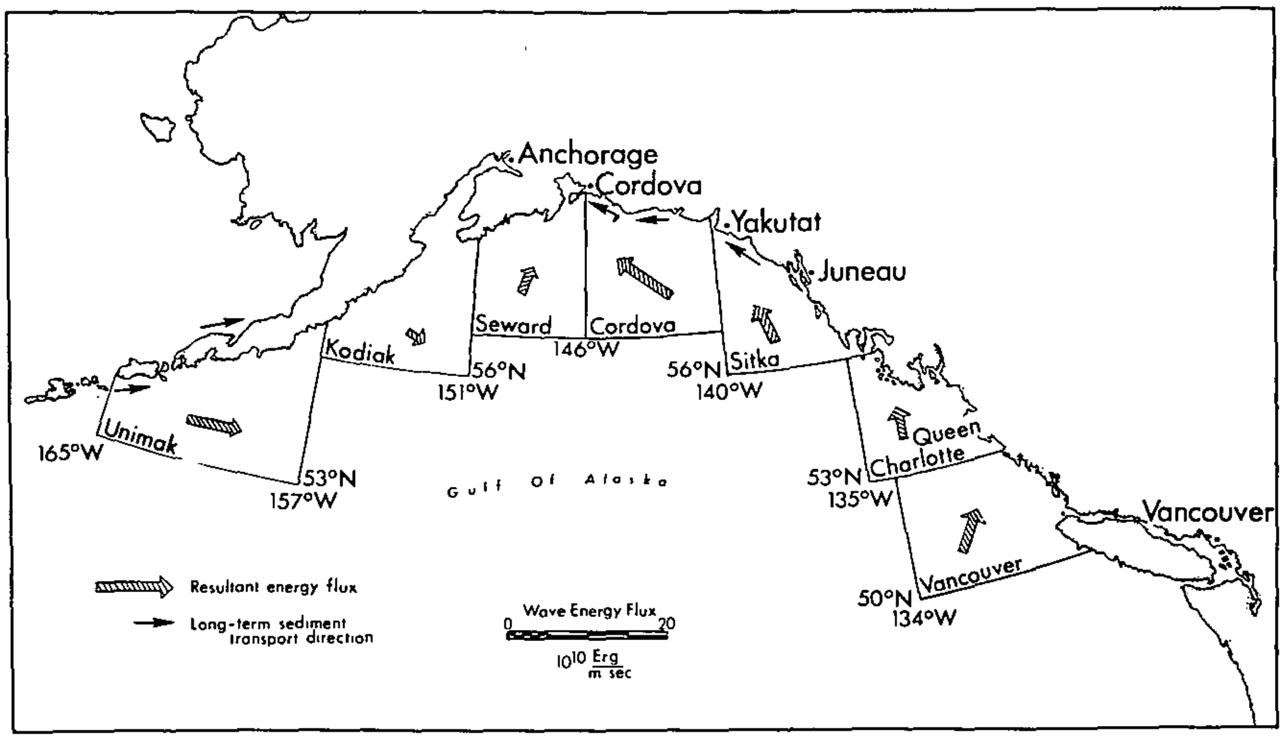


FIGURE 11. Resultant wave-energy flux distribution and longshore sediment transport directions (based on large-scale geomorphic features) for the coastal areas of the Gulf of Alaska (from Nummedal and Stephen, 1976, Fig. 19). The resultant wave-energy flux was determined by vectorial addition of values for each compartment shown, which are based on deep-water wave observations. Note the convergence of wave-energy flux toward the PWS area.

the coastal morphology shows a strong response to the resulting westerly longshore transport in the form of elongated spits, downdrift offsets of tidal inlets, and orientation of coastal dunes. This pattern does not hold for the Outer Kenai and Kodiak areas, however, where complex orientations result from a diversity of local winds. Northwesterly winds, and resultant wave energy flux toward the southeast, become more important further out the Alaska Peninsula (Fig. 11).

According to Brower et al. (1977), large storms on the south-central Alaskan continental shelf generate waves of the following magnitude: significant wave heights - 5-year recurrence equals 13 m and 100-year recurrence equals 22 m; extreme wave heights - 5-20 years recurrence equals 22-40 m. Again, we can only speculate about the exact magnitude of the recurrent waves within PWS.

Tides

As can be seen by the two representative tidal curves in Figure 12, a wide range in tidal conditions occurs within PWS. The mid-October 1989 spring tides shown in Figure 12A, some of the largest of the year, achieved a maximum range of 18 feet (5.5 m). On the other hand, neap tides of early November 1989 had a range of only 7.5 feet (2.3 m). Another important aspect of the tides of PWS is their large diurnal inequality, with low-low tides and high-low tides sometimes differing by up to a meter (Fig. 12B). The differences of the tidal magnitudes, plus the diurnal inequality, made scheduling of the field visits during the fall and winter months difficult, because of the limited number of hours of daylight. All trips were scheduled during spring tides, but the low-low tides did not always fall during daylight hours. Consequently, it was not possible to survey the lower intertidal zone during every visit.

Currents

The oceanic currents on the continental shelf off the spill site are controlled by the westward flowing Alaska Coastal Current, which has a mean speed of 50-100 cm per second (Hampton et al., 1986; Reed and Schumaker, 1986). As seen on the map in Figure 13, the current hugs the shoreline from the entrance to PWS to beyond Kodiak Island (staying within 20 km of the shoreline), which accounts, at

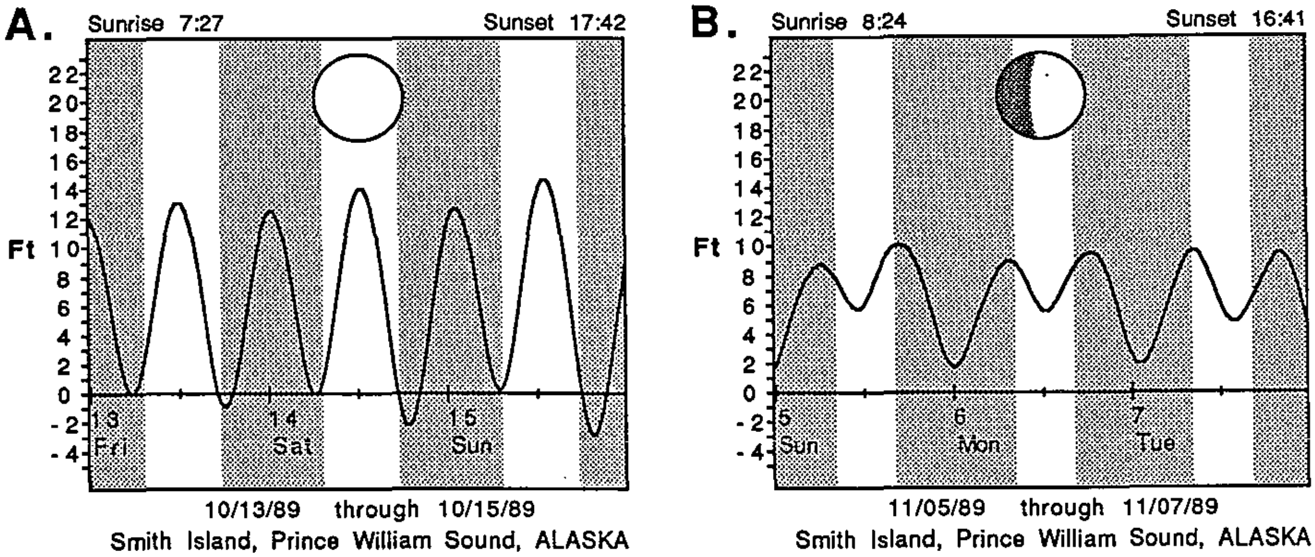


FIGURE 12. Representative tidal curves for the Smith Island area of PWS.

A. Large spring tides of 13-15 October 1989.

B. Small neap tides of 5-7 November 1989. Note extreme diurnal inequality.

least in part, for the extreme length of shoreline oiling that resulted from the EXXON VALDEZ spill.

Part of the Alaska Coastal Current enters PWS through Hinchinbrook Entrance, which has predominantly inflow, especially at the surface (Royer et al., 1990). Thus, most of the water exiting PWS must do so through the southwestern passages, which have predominantly outflow. Freshwater discharge into the sound drives a cyclonic circulation cell within PWS. The currents are weak in the northern Sound (<10 cm per second) and westward, eventually heading to the south-west to flow on either side of Knight Island. Most of the water exits through Montague Pass, though there is some flow through the narrow (<2 km) and shallow (<35 m deep) passages to the west, called Latouche, Elrington, Prince of Wales, and Bainbridge. Surface flow velocities out Montague Pass vary seasonally from less than 20 cm per second to more than 150 cm per second (Royer et al., 1990). The large tidal range in PWS also generates strong currents, which achieve velocities of several knots in some of the straits and entrances.

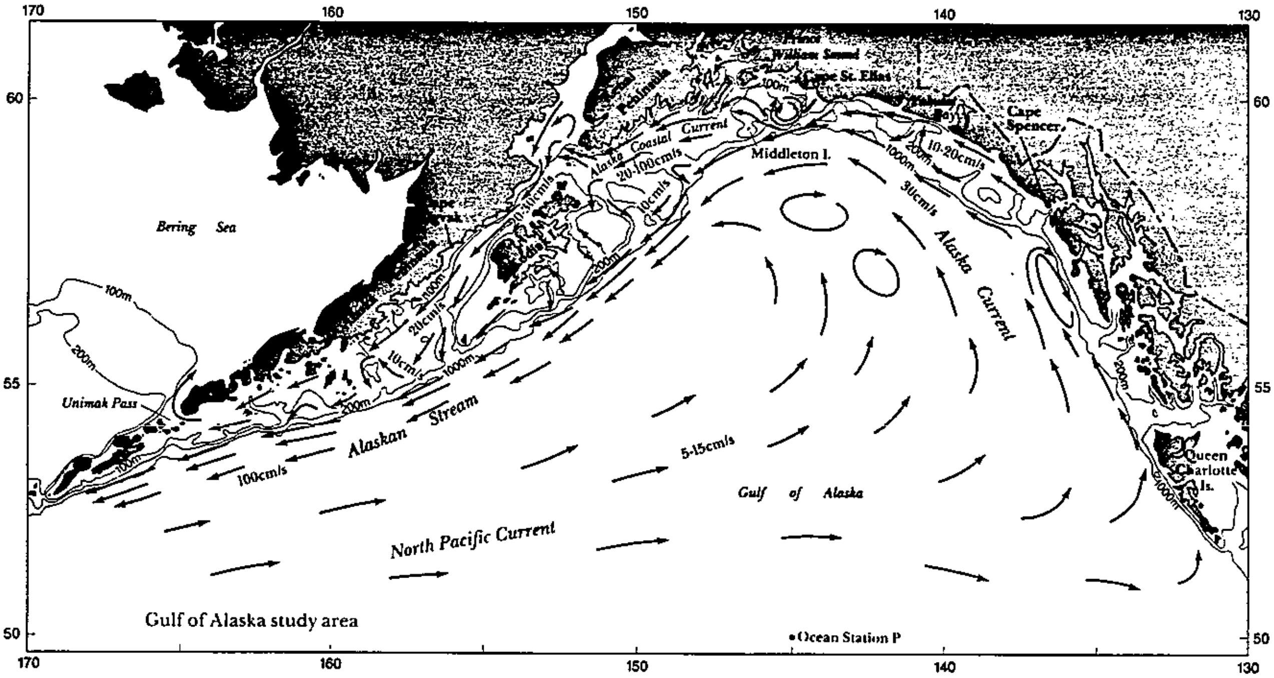


FIGURE 13. General distribution of the major currents in the Gulf of Alaska. Note impingement of the Alaska Coastal Current against the coastline impacted by the EXXON VALDEZ spill (from Reed and Schumaker, 1986; Fig. 31).

COASTAL MORPHOLOGY

The coastal morphology of the four coastal regions impacted by the spill has been studied in some detail by the authors over the years, with much of this work providing the baseline geomorphic data for RPI's Environmental Sensitivity Index (ESI) maps produced while under contract to NOAA. A map showing the geographical areas of the ESI mapping projects by RPI in Alaska is given in Figure 14. Some of the key references that document these geomorphological studies of south-central Alaska follow:

	Region		References
1)	Lower Cook Inlet	—	Hayes, Brown, and Michel (1976); Hayes and Michel (1982); Michel, Hayes, and Brown (1978); Hayes and Michel (1989)
2)	Outer Kenai Peninsula	—	Hayes (1980); Ward et al. (1987)
3)	Kodiak	—	Ruby et al. (1979); Finkelstein (1982)
4)	Shelikof Strait	—	Domeracki et al. (1981)
5)	Copper River Delta to Yakutat	—	Hayes et al. (1976a); Ruby (1977); Ruby and Hayes (1978); Hayes et al. (1976b); Hayes and Michel (1989)

No summary publication was written to supplement the ESI mapping in PWS, which was carried out in the summer of 1983. In addition to the detailed ESI maps (using 1:63,360 scale base maps), which contained critical seasonal data on the biological resources at risk in PWS, a series of seasonal summary maps had also been prepared. Both of these map tools were available and widely used at the time of the spill. In fact, this was the first spill at which the need for various scales of sensitivity maps was so great.

A basic component of the ESI Index is a numerical scale (1-10) of the primary geomorphic units in an area. The distribution of the different ESI classes in the areas impacted by the spill, except Lower Cook Inlet, is illustrated in Figure 15, and detailed shoreline lengths for each type are given in Table 2. The numbers for PWS were calculated only of the coastline area that was oiled during the EXXON VALDEZ spill.

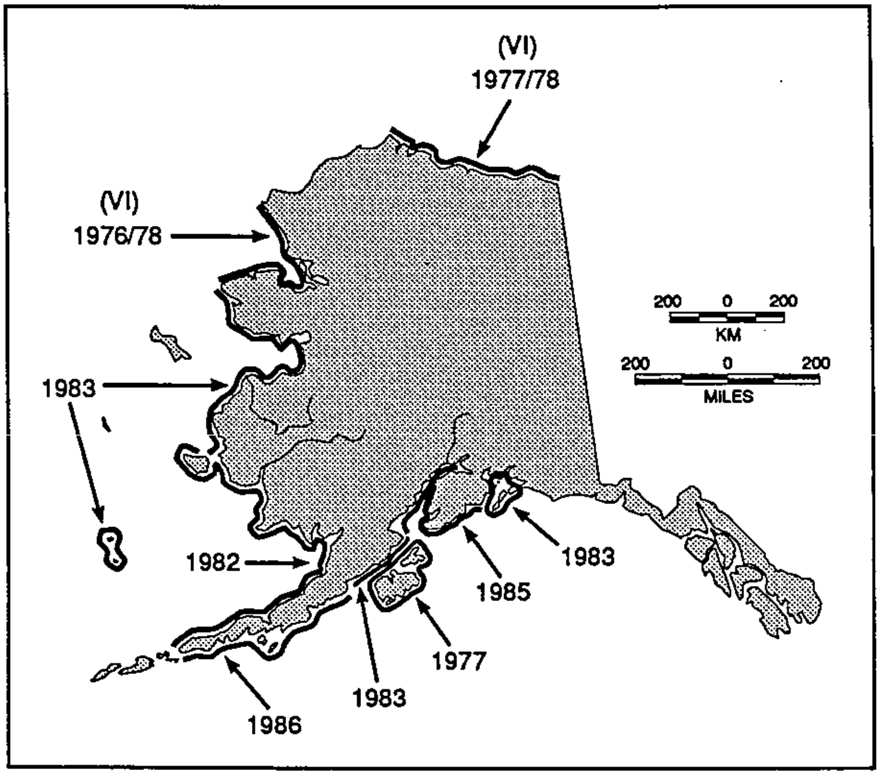


FIGURE 14. Areas of the coast of Alaska mapped for environmental sensitivity by RPI. The dates shown indicate years when field work was carried out. The areas marked with VI have only the shoreline mapped, with no biological data on the maps.

The data in Figure 15 and Table 2 show several general trends for the impacted area:

1) Exposed rocky coasts and wave-cut rock platforms, ESI coastal types 1 and 2, are quite abundant in each area, ranging from 23 percent in PWS to 38 percent on the Outer Kenai. The higher numbers for the Outer Kenai, 10 percent higher than any other area, no doubt reflect the greater exposure of that coastline to large waves.

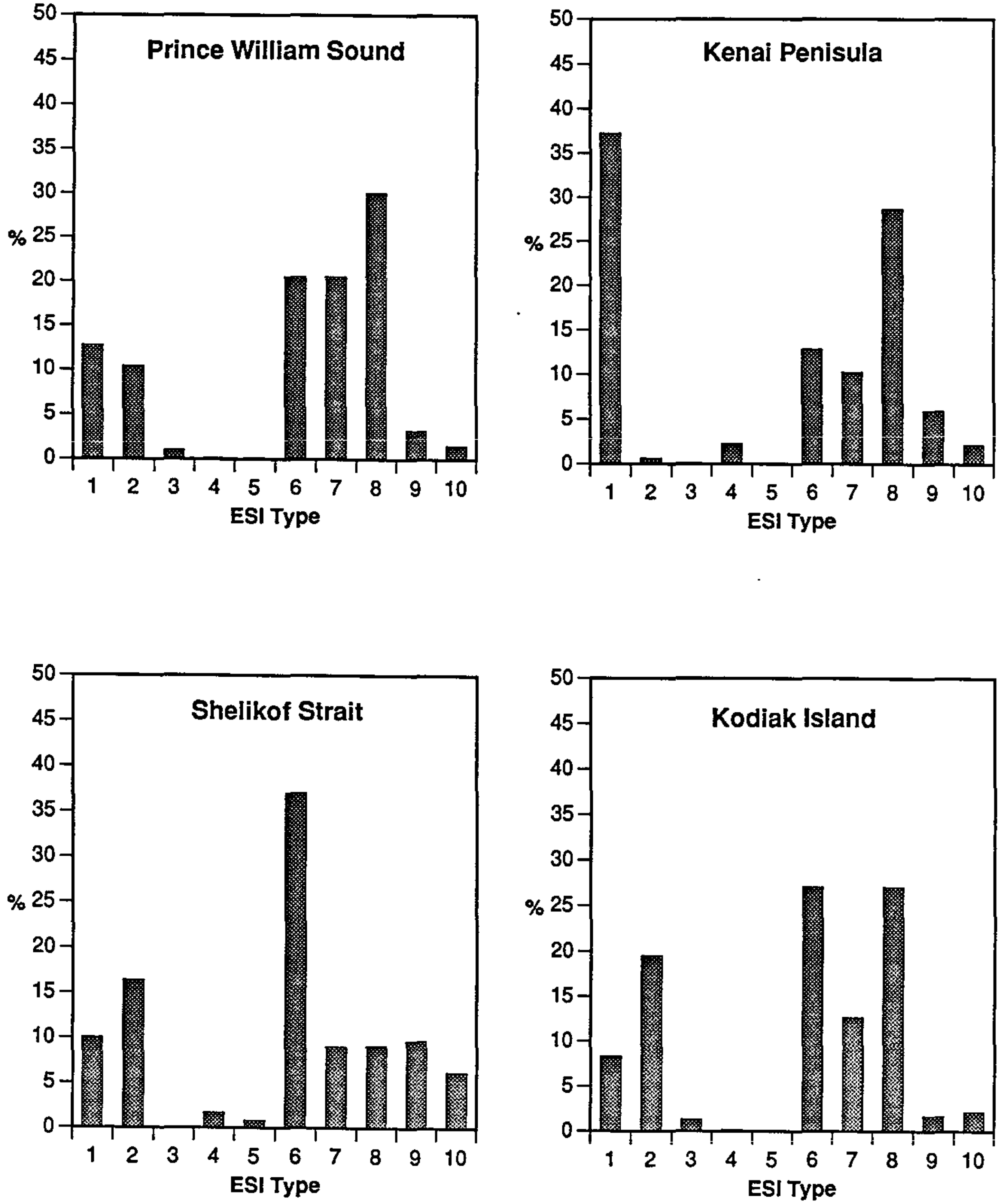


FIGURE 15. Occurrence of ESI coastal types within the major coastal areas of Alaska impacted by the EXXON VALDEZ oil spill, except Lower Cook Inlet.

2) Fine and coarse sand beaches, ESI coastal types 3 and 4, make up between one and two percent of the coastline in every area. This is the result of the absence of major river systems and depositional coastlines in general.

3) Exposed tidal flats, ESI type number 5, makes up less than one percent of the coastline in every area. This is, again, a result of either the presence of large waves or absence of major depositional systems, or a combination of the two.

4) Mixed sand and gravel and gravel beaches, ESI types 6 and 7, make up 40-46 percent of the shoreline of all the areas, except the Outer Kenai (23 percent). The combination of eroding rocky coasts and glacial sediment sources account for these high numbers.

5) Sheltered rocky coasts, ESI coastal type number 8, are abundant (27-30 percent) everywhere except on the west shore of the Shelikof Strait (9 percent).

6) Sheltered tidal flats and salt marshes, ESI coastal types 9 and 10, are relatively scarce (4-7 percent) everywhere except the west coast of Shelikof Strait, where they compose 16 percent of the coastline. The presence of several large drowned glacial valleys with stream outlets in the Shelikof region accounts for both the higher percentages of sheltered tidal flats and marshes and lower percentages of sheltered rocky coasts in that area.

The coastline in PWS that was impacted by the spill was completely dominated by three of these genetic categories: (1) sand and gravel plus gravel beaches (41 percent); (2) sheltered rocky coasts (30 percent); and (3) exposed rocky coasts and rock platforms (23 percent). The study sites that were chosen are a good representation of these coastal types.

TABLE 2. Occurrence of ESI coastal types within four of the coastal regions of Alaska impacted by the EXXON VALDEZ oil spill. Numbers represent kilometers of each shoreline type present.

Number ESI	PWS	%	Kenai Peninsula	%	Shelikof Strait	%	Kodiak Is.	%
Exposed Rocky Coasts								
1	322	12.7	505.7	37.2	243	10.0	190.5	8.3
Exposed Wave-cut Rock Platforms								
2	263	10.4	7.63	0.6	402	16.4	450	19.5
Fine-grained Sand Beaches								
3	26.5	1.0	1.85	0.1	1.0	0.04	30	1.3
Coarse-grained Sand Beaches								
4	4.0	0.1	29.4	2.2	42	1.7	5.4	0.2
Exposed Tidal Flats								
5	2.6	0.1	1.8	0.1	20.8	0.8	3.2	0.1
Mixed Sand and Gravel Beaches								
6	517	20.5	173.5	12.8	911	37	623.2	27.0
Gravel Beaches								
7	517	20.5	138.5	10.2	223	9.0	291.3	12.6
Sheltered Rocky Coasts								
8	758	30	389	28.6	222	9.1	623.6	27.0
Sheltered Tidal Flats								
9	80	3.2	80.8	5.9	239	9.7	39.9	1.7
Salt Marshes								
10	38	1.5	28.6	2.1	154	6.2	48.1	2.1
TOTAL	2,528		1,353.5		2,459		2,305.5	

METHODS OF STUDY

STATION SELECTION

Two field teams were deployed into PWS in September 1989 to select study sites and conduct the first field survey. The eighteen stations selected (Fig. 16) were thought to be representative of the various shoreline types, degree of exposure, and treatment technologies used. All of the stations were classified as moderately to heavily oiled. Table 3 lists the stations by number, location, and type. It should be noted that seven stations are exposed to relatively high energy, six are classified as sheltered, and five fall into the intermittant-energy classification. Three stations (N-5, N-6, and N-13) are located in set-aside segments which received no treatment by Exxon during the 1989 summer. It is anticipated that these sites will continue to be set-aside from treatment for scientific study purposes. NOAA was not able to deploy additional field teams to conduct winter monitoring in the Seward, Homer, and Kodiak districts.

During the spring and summer studies of 1990, several additional stations were added. The four sites shown in Figure 17 were chosen as being representative of conditions in the Outer Kenai area. A detailed study was carried out on the exposed gravel beach at US-5 on Ushagat Island in the Barren Islands. This station contrasted well with the new one located on the sheltered beach at the head of Port Dick (PD-1) and the one located on the delta in front of the Yalik Glacier (YG-2). The station CI-1A on Chugach Island was visited by Hayes during the SSAT survey in April 1990.

In order to compare gravel beaches of different energy levels in the PWS area, another somewhat sheltered beach, N-16Y on Applegate Island, was surveyed in June 1990. This beach served as an excellent contrast to PB-1, which was established on the outer coast of Montague Island in May 1990 (Fig. 16). Geological studies were carried out in September 1990 at 4 of the 24 stations established by the biological field team during the summer of 1990 - Bass Harbor, Shelter Bay, Sheep Bay, and Crab Bay (Fig. 16).

TABLE 3. List of NOAA stations established in Prince William Sound as part of the winter and summer monitoring program.

Station Number	Location Name/ Segment Number	Degree of[1] Exposure	Initial[2] Oiling	Type of[3] Treatment
N-1	Pt. Helen KN 405	E	H	W, B
N-2	Green Island GR 103	E	M	W, B
N-3	Smith Island SM 06	E	H	W, B, R
N-4	Smith Island SM 05	E	H	W, B, R
N-5	Snug Harbor-Inside KN 401	S	M	Set-Aside
N-6	Bay of Isles, West Arm KN 208	S	M-L	Set-Aside
N-7	North of Bay of Isles KN 211	E	H	W, B
N-8	Eleanor/Block Is. East EL 10	I	H	W
N-9	Eleanor/Block Is. West EL 11	I	H	W, B
N-10	NE Herring Bay KN 113	I	H-M	W, B
N-11	Crafton Island CR 05	S	M	W, B
N-12	Crafton Island CR 05	S	M	W, B
N-13	E Herring Bay KN 5000	S	M	Set-Aside
N-14	Northwest Bay EL 52	S	H	W, B
N-15	East Latouche Island LA 15	E	H	B, R
N-16	Applegate Island AE 04	I	M	W, B
N-16Y	Applegate Island AE 04	I	M-L	W, ?
N-17	Perry Island PR 16	E	H	W, B, R
N-18	Sleepy Bay LA 18/19	E	H	W, B, R
	Shelter Bay	I	M	W, B
	Crab Bay	S	O	None
	Sheep Bay	S	O	None
	Bass Harbor	I	VL	None
PB-1	Montague Island	E	O	None

[1] S = Sheltered; I = Intermittant; E = Exposed

[2] H = Heavy; M = Medium; L = Light; VL = Very Light; O = Clean

[3] W = Warm-to-Hot-Water Wash; B = Bioremediation; R = Berm Relocation. In 1990, all oiled sites except the set-asides were treated with bioremediation.

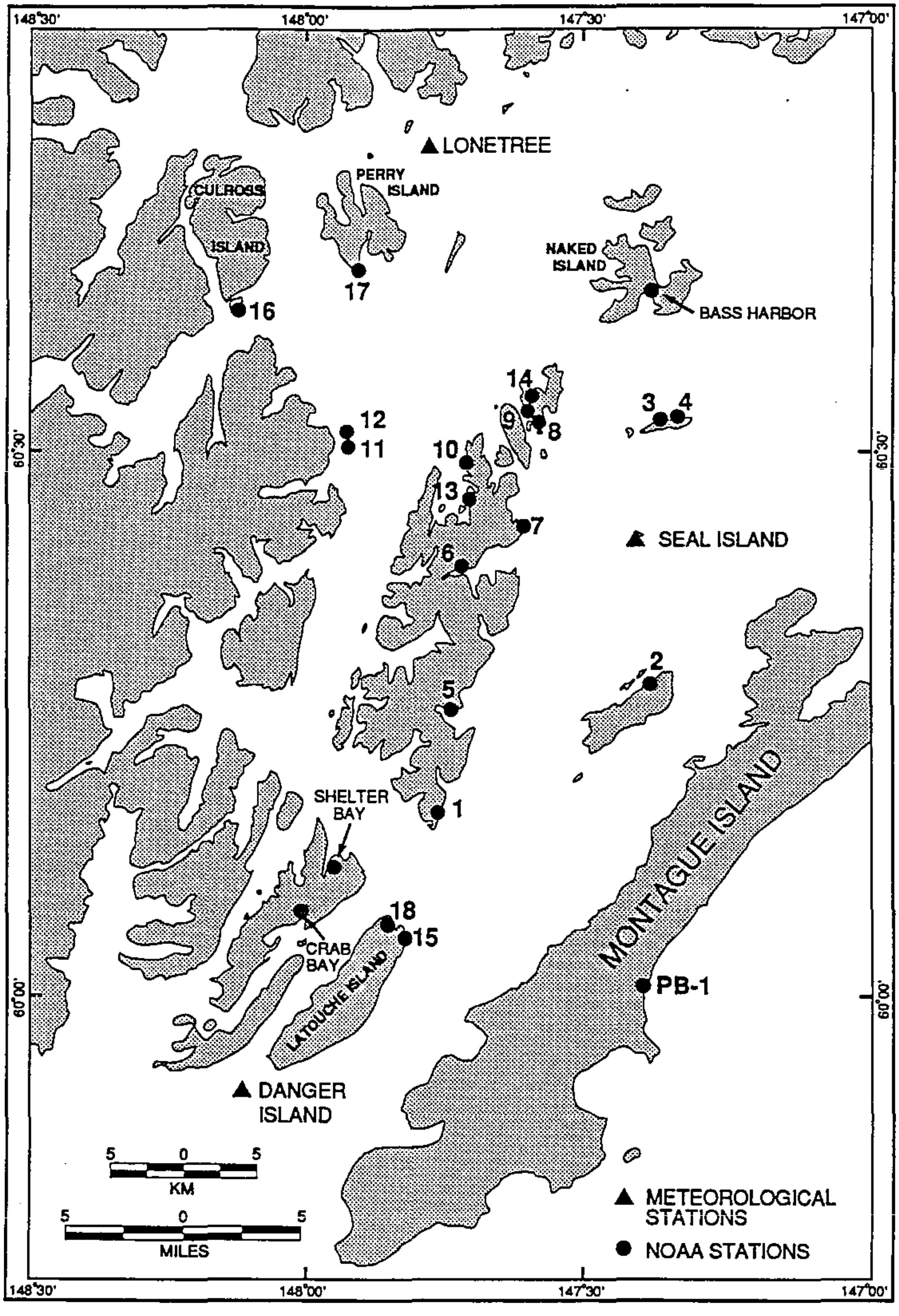


FIGURE 16. Location of the study sites and meteorological stations in PWS. The numbers refer to the original 18 NOAA stations. The named sites are those biological stations added in September 1990. A fourth biological station, Sheep Bay, is located in eastern PWS.

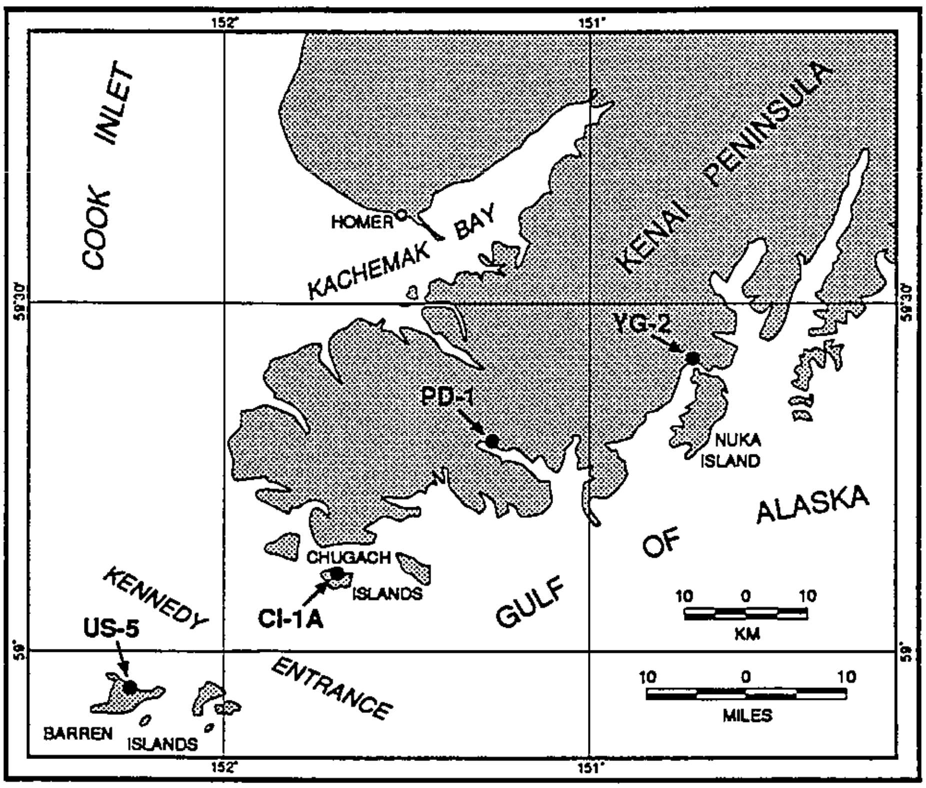


FIGURE 17. Location of the principal study sites in the Outer Kenai Peninsula area.

FIELD DATA COLLECTION

The permanent stations were visited a total of 9 times between September 1989 and September 1990. As can be seen in Table 4, it was not possible to visit all 18 stations on every trip, because of weather or other logistical problems. Exxon provided a variety of logistical conveyances, which included both boats and helicopters.

During each visit, the following data were collected at a station:

1) <u>A topographic profile run perpendicular to the beach</u>. A stake was driven behind the high-tide line as a reference point from which all profiles were run. Along this profile, the location of zones, trenches, and samples were noted. Oil distribution and sediment type for each interval were recorded. Starting in May 1990, all profiles were "closed", that is, the profile was run in reverse back up the line. The profile was immediately re-surveyed if the vertical difference was greater than 5 cm.

2) <u>Visual estimates of the surface oil coverage</u>. For each interval, which varied between surveys, an estimate of the surface oil coverage was made. Notes were recorded as to thickness and character of the surface oil.

3) <u>Depth of penetration of subsurface oil</u>. Trenches were dug at several locations along the profile to determine the depth of oil penetration. Each trench was described and photographed. Many times it was not possible to dig the trench to reach clean sediments because of the shallow water table in the beach.

4) <u>Samples for oil quantification and characterization</u>. Sediment samples were collected of both surface and subsurface oil contamination. In some cases, surface samples were individual clasts placed into the sample jars for analysis, mostly for detailed characterization and analysis of weathering trends. In most all other cases, the surface samples represented the top 2 cm of sediment. Only those samples from the top 2 cm are listed in the station tables on oil content of sediment samples. 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; the samples are all "grab" samples. All samples are numbered sequentially, with surface samples denoted 'A' and subsurface samples denoted 'B'. Samples were

TABLE 4. Listing of the survey dates and stations visited during the NOAA winter and summer monitoring program.

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

collected with clean scoops and placed in pre-cleaned glass jars with teflon-lined caps.

5) Detailed sketch of the station. The station was sketched in detail, highlighting the distribution of oil relative to the shoreline geomorphology and showing the location of zones, trenches, and samples.

6) Photograph and videotape documentation. Detailed photographs and videotapes were made at each station during the fall and winter surveys. The videotaping was discontinued after the March 1990 survey.

7) Detailed sediment studies. Starting with the May 1990 survey, visual estimates were made of the surface sediments at each survey point on the profile, using the visual estimate chart presented in Figure 18. Detailed measurements of the size, shape, and roundness of individual gravel clasts were made at some of the stations in June 1990. Roundness was estimated by comparing the clast with the roundness chart given in Figure 19.

8) Zonal studies. The zone of study was expanded at four of the stations, N-15, US-5, N-18, and YG-2, by running two additional profiles on either side of the primary station. This allowed for the construction of a three-dimensional plot of the area.

LABORATORY ANALYSIS OF SEDIMENT

All sediment samples were kept in coolers in the field and later transferred to freezers for storage until they were shipped to the laboratory. Chain-of-custody was maintained for all samples.

FIGURE 18. (Facing page) Visual estimate chart for determining the average grain size of surface sediments at the survey sites along a beach profile. A laminated version of this chart is laid on the sediment surface as each estimate is made. Designed by David C. Noe.

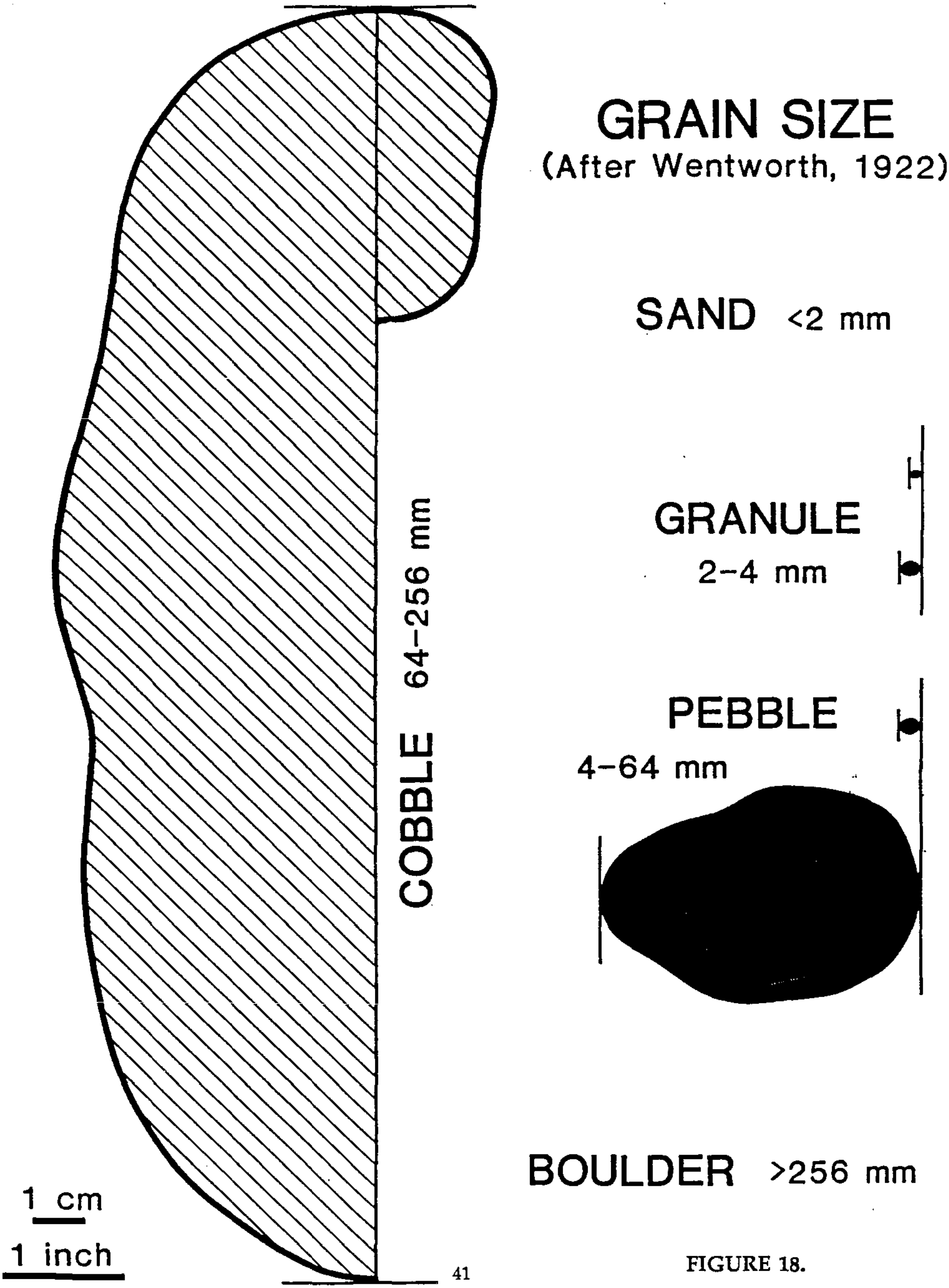

GRAIN SIZE
(After Wentworth, 1922)
SAND <2 mm
GRANULE
2–4 mm
PEBBLE
4–64 mm
COBBLE 64–256 mm
BOULDER >256 mm
1 cm
1 inch

FIGURE 18.

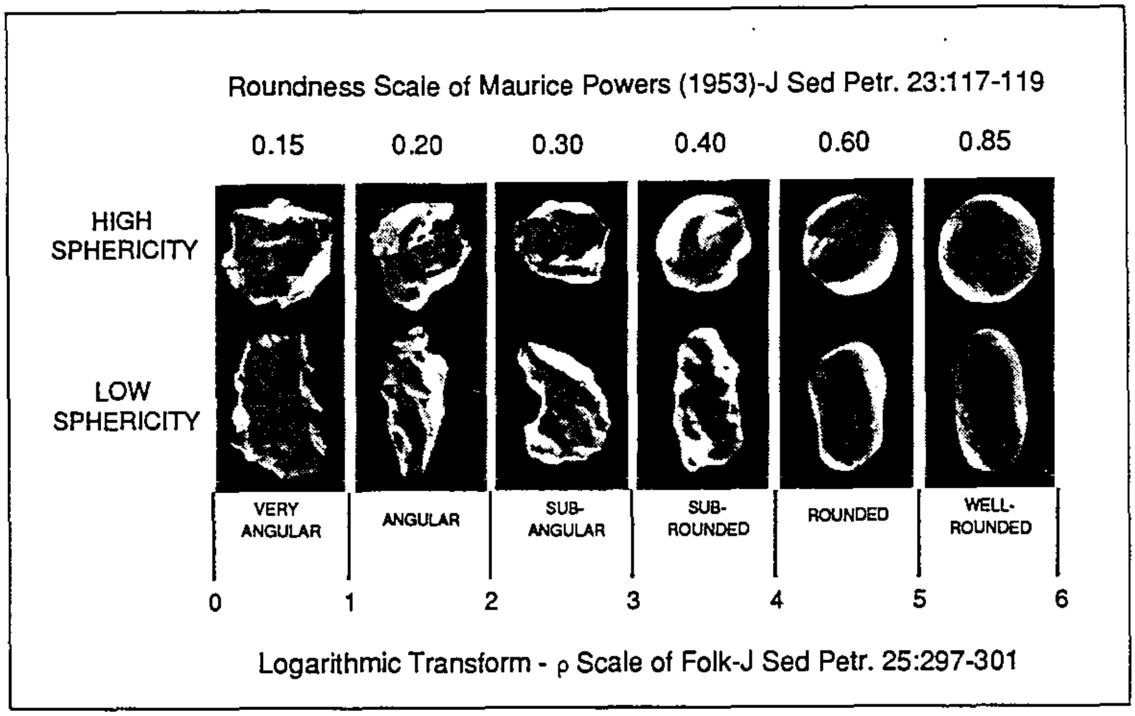


FIGURE 19. Chart for making visual estimates of roundness for individual clasts. The scale of Folk (1971) was used in our calculations.

Louisiana State University (LSU) performed all the laboratory analyses. Two types of analyses were conducted. Total petroleum hydrocarbon (TPH) was measured on all samples using the gravimetric method (Standard Method 503) on extracts from subsamples. Solvent-rinsed #40 Whatman filter papers were used during filtering to assure removal of fine-grained sediments. Selected samples were also analyzed by gas chromatography/mass spectrometry (GC/MS) for detailed characterization of individual compounds. GC/MS data are not included in this report

STATION PROFILE DATA

The profile data for each station were entered into an Excel™ spreadsheet and 100 percent error checked. The topographic profiles were plotted from the same reference point as two-month comparisons, to show monthly changes in the morphology at the station, and for all months, to show the "sweep" of all the changes. The grain-size estimates were plotted at the same scale as the topographic profiles and show the relative percentages of the surface sediment by the classes of boulder, cobble, pebble, granule, and sand.

The trends in surface oil coverage estimated at each station are shown in two different kinds of plots. First, the actual oil coverage estimate for each interval is plotted against distance down the profile. These plots can be for sequential months, all months, or the first and last months, depending on how complicated the oil distribution patterns are. They are helpful to discern the differences in the rate of natural oil removal from the upper, middle, and lower parts of the profile. The second kind of plot is an integration of the surface oil coverage for each month. The monthly value is calculated by the formula:

$$T_{so} = \sum \quad [(d_i o_i) \div 100]/D$$

T_{so} = total surface oil

d_i = distance for each interval along the entire profile

o_i = percent surface oil coverage

D = total profile length

With the data plotted in this manner, the monthly trend in overall changes in surface oil can be determined. It should be noted, however, that the surface oil coverage plots do not reflect changes in surface oil thickness, only the coverage. Thus, the plots do not indicate removal by thinning of the oil coating.

The depth of oil penetration is a much more difficult parameter to analyze. The trenches were dug at various locations representative of the upper, middle, and lower intertidal zones. Many times it was not possible to dig the trench to reach visibly clean sediments, so these depths were indicated as minimum depths.

GRAVEL BEACHES: A SPECIAL PROBLEM

INTRODUCTION

Much of the oil spilled by the EXXON VALDEZ came ashore along gravel beaches, both inside and outside of PWS. Gravel beaches present a special problem with regard to the behavior and fate of spilled oil that impacts them. Oil penetrates gravel readily and the potential for burial of oil and the formation of asphalt pavements is enhanced by the presence of gravel (Owens, 1971; Hayes and Gundlach, 1975). Gravel beaches were also impacted heavily at the METULA (1974) and AMOCO CADIZ (1978) oil spills. This section of the report, which is based on the authors' experience at the METULA, AMOCO CADIZ, and EXXON VALDEZ spills, as well as studies of gravel beaches in several other locations around the world, presents a brief introduction to the morphology and sediment character of gravel beaches, a description of how oil behaves on gravel beaches, and a statement of some of the more critical problems related to oil on gravel beaches.

As used here, the term gravel beach means any beach containing coarse-grained sediments subject to waves that will move the coarse material on an annual basis. The shoreline sediment must contain at least 15-20 percent of particles greater than 4 mm in diameter, ranging up to large boulders. Sedimentologists (e.g., Folk, 1974) divide gravel into four classes as follows:

Class	Size Range
granule	2-4 mm
pebble	4-64 mm
cobble	64-256 mm
boulder	greater than 256 mm

The term "rock" is commonly used at oil spills to refer to gravel, but we recommend that the term be restricted to bedrock or possibly large rubble at the base of cliffs.

The results from the ongoing monitoring of the gravel beaches in PWS oiled by the EXXON VALDEZ spill show a variety of responses of those beaches to natural cleansing mechanisms. Because these types of beaches are quite common in Alaska, as well as other subpolar and temperate regions, a better understanding of them is needed for adequate spill response in the future.

OCCURRENCE OF GRAVEL BEACHES

Gravel beaches are most common along two types of shorelines–glaciated coasts and rocky, mountainous coasts. Coasts now subject to glaciation, such as the south-central coast of Alaska, typically have abundant gravel and sand plus gravel beaches along up to 40-50 percent of their length (Table 2) as a result of glacial outwash streams depositing gravel at the coastline or of waves eroding coarse material brought directly to the coast by the ice itself (e.g., end moraines). Areas subjected to Pleistocene glaciation, which includes much of the temperate to subpolar regions of the Northern Hemisphere, also have abundant gravel deposits where the relict glacial deposits are eroding. Erosion of rocky, mountainous coasts, such as those that occur on parts of the outer coasts of Oregon, Washington, and California, also tends to produce abundant gravel beaches. There are several other mechanisms whereby gravel can be made available to waves on beaches, such as marine ice gouge in polar regions. As a result, gravel beaches are widely distributed along the shorelines of the world, particularly the temperate and subpolar areas of the Northern Hemisphere.

CONTROLS OF NATURE OF GRAVEL BEACHES

Gravel beaches are complex features, the physical character of which is controlled by a number of variables. The concept of degrees of freedom has been used by others to summarize the controls of the morphological and sediment-ological character of river deposits (e.g., Hey, 1982), and it can be applied as well to gravel beaches (see Table 5). The dependent variables of a gravel beach include such factors as the beachface slope, variations of beach morphology, including berms, presence of swash bars, and other features, the volume of sediment occurring in the beach system, size distribution and sorting of the sediments, and the internal characteristics of the sediment body. These fixed or dependent variables will respond to changes in a number of independent variables, such as wave height, wave character (e.g., reflective/dissipative), volume and type of sediment available through time, the nature of storms impacting the beach, and tectonic setting. In short, the gravel beach is a dynamic system that responds on a short-term basis, sometimes measured in seconds, to the input of a wide range of independent variables.

TABLE 5. Degrees of freedom on a gravel beach.

Fixed (dependent) variables	
1.	Beachface slope
2.	Beach morphology (berms, swash bars, etc.)
3.	Intertidal sediment volume
4.	Size distribution and sorting parameters of sediments
5.	Vertical layering by sediment type
Independent variables	
1.	Wave height (average size, duration, etc.)
2.	Wave character
	a) breaker type (plunging, spilling, collapsing)
	b) Energy dispersion (reflective/dissipative waves)
	c) Edge waves
3.	Volume and type of sediment available through time
4.	Tidal range
	a) Maximum/minimum; timing
	b) Diurnal inequality
5.	Nature of storms
6.	Wave-generated currents (swash, alongshore)
7.	Substrate type
8.	Rock platform slopes (if present)
9.	Tectonic adjustments (time factored)
10.	Water density and volume of suspended sediments

The response of sand beaches to changes in independent variables such as those listed in Table 5 is fairly well understood. Work begun during World War II showed that sand beaches follow a well-documented beach cycle related usually to the passage of storms, with sand being carried offshore during the storm and onshore during post-storm recovery (e.g., Shepard, 1950; Hayes and Boothroyd, 1969). Gravel beaches, on the other hand, may retain an arrested, swell profile, which is maintained through storm periods (Carter and Orford, 1984). In fact, under many storm conditions, gravel is transported landward rather than seaward.

Sediment transport and remobilization on gravel beaches is a poorly understood process. Studies such as the ones by Carr (1971), Caldwell (1981), and Hattori and Suzuki (1978), give good indications of sediment transport directions and general clues concerning the wave parameters involved. However, their data cannot be used to calculate volumetric sediment discharges or to derive specific predictions as to the nature of the detailed sorting and transportation processes. The practical need for research on gravel beaches has not been as great as for sand beaches, where numerous projects to deal with beach erosion have been initiated by such groups as the U.S. Army Corps of Engineers (e.g., Everts and Czerniak, 1977). Problems encountered with oil spill cleanup, particularly at the EXXON VALDEZ spill site, have provided a real need for a better understanding of gravel beaches.

Regardless of these shortcomings in our understanding of gravel beaches, we do know that the internal character of waves is one of the most important determinates of the nature of both sand and gravel beaches. The beach is a three-dimensional sediment body made from material carried to the site by wave-generated currents that flow both parallel with and perpendicular to the shore. Studies in recent years on the microtidal (tidal range < 2 m) sandy beaches of Australia, exemplified by Wright et al. (1979), have provided a detailed accounting of the three-dimensional variability of high-energy sandy beaches. These studies placed emphasis on the reflective and dissipative nature of sandy beaches, based on extensive field measurements of surf and inshore current spectra and inshore circulation patterns.

According to Wright et al. (1979, p. 105), reflective sandy beaches are characterized by steep, linear beachfaces, well-developed berms and beach cusps, and surging breakers with high runup and minimum setup; rip cells and associated three-dimensional inshore topography are absent. Dissipative sandy beaches are typically found on open coasts and are characterized by concave-upward nearshore profiles and wide, flat surf zones which may contain multiple bars. Waves break tens of meters seaward of the beach and dissipate much of their energy before reaching it.

Following the lead of Massari and Perea (1988), who applied the concept of reflective/dissipative beaches to some ancient progradational gravel beach sequences in Italy, we have applied the concept to the gravel beaches at the EXXON VALDEZ spill site. We believe that gravel beaches formed under the two different wave regimes at the spill site have the following characteristics:

<u>Wave Regime</u>	<u>Characteristics of Gravel Beaches</u>
REFLECTIVE	- clear evidence of sorting effects (size and shape) on steep beachfaces - multiple cuspate berms - narrow directional width of incoming wave spectrum, which is always shore normal
DISSIPATIVE	- strong evidence of longshore transport, barred morphology, and rip development - frequent shifts in wave conditions (approach and type) - limited swell effects

Some beaches are permanently reflective and others are permanently dissipative. Dissipative gravel beaches, which are characterized by oblique wave approach and flat near-shore topography, have the potential for oil to be buried under landward migrating swash bars and laterally migrating rhythmic topography (Fig. 20). Some gravel beaches are host to both dissipative and reflective wave conditions (Fig. 21). Dissipative waves are more common during storms and reflective waves during calmer periods. During the dissipative storm wave conditions, spilled oil may be carried high into the storm berm environment, where it would penetrate into the coarse material, whereas during reflective, recovery conditions, oil could be buried under the developing berms.

The distinction between reflective and dissipative gravel beaches, though still in need of refinement, is an important one. This distinction should be considered for inclusion on maps compiled during future contingency planning for oil spills.

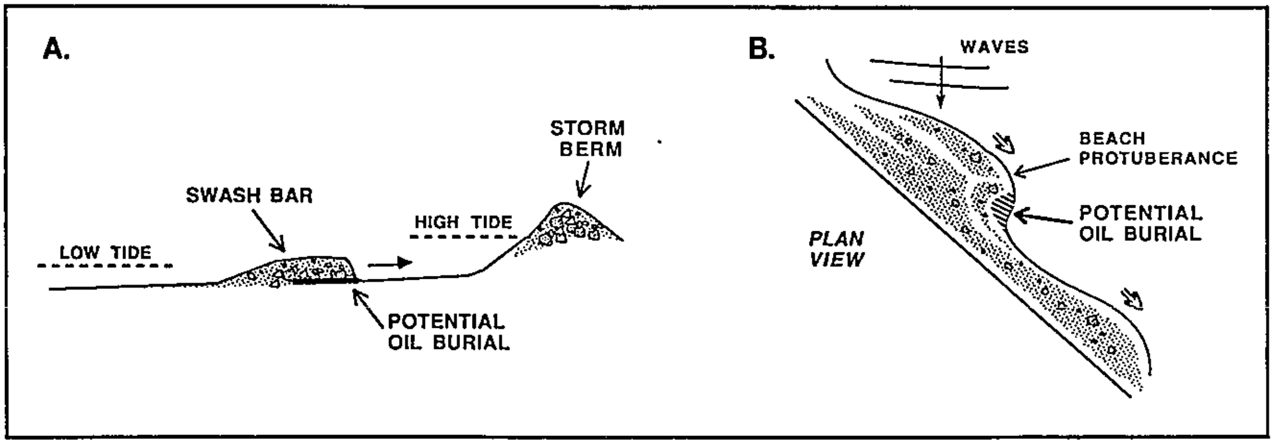


FIGURE 20. Two types of potential oil burial at permanently dissipative gravel beaches. In both examples, a mass of sediment in motion buries oil deposited at an earlier time. Oil burial by laterally migrating rhythmic topography (Diagram B) was observed at both the METULA (1974) and EXXON VALDEZ spill sites and oil burial by landward migrating swash bars (Diagram A) was observed at the EXXON VALDEZ spill site.

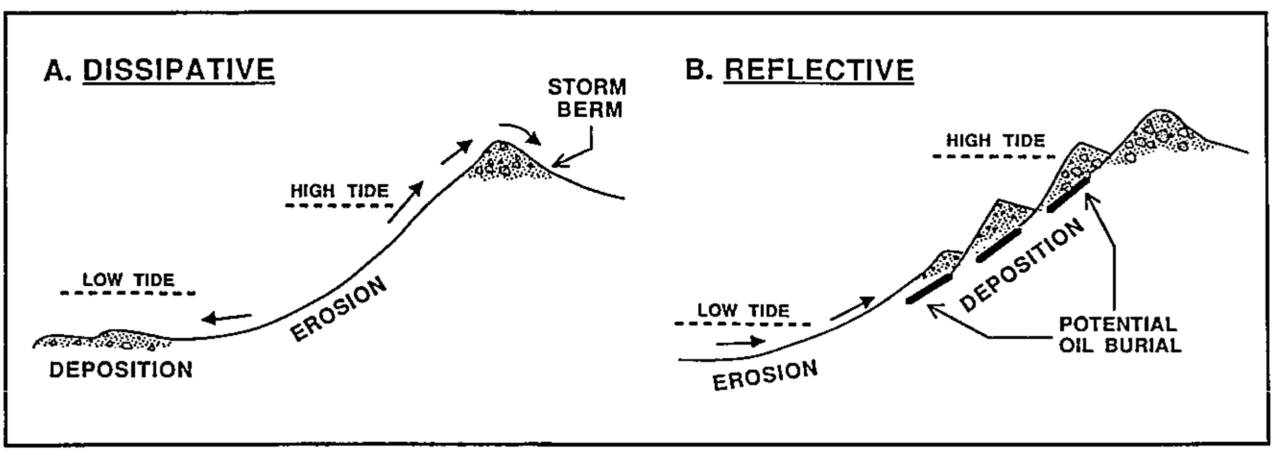


FIGURE 21. Examples of types of changes in beach morphology at the same gravel beach during dissipative and reflective wave conditions. Dissipative waves prevail during storms and reflective waves are present during calmer periods on gravel beaches of this type. Note sites of potential oil burial at base of post-storm, constructional berms, a process observed at the EXXON VALDEZ spill site.

ARMORING OF GRAVEL BEACHES

A stable armor of coarse material develops over the surface of the middle and lower portions of many gravel beaches. Whereas the process of armor formation has been studied on gravel bars in rivers (e.g., White and Day, 1982), the authors know of no such study on beaches. Armoring of a gravel beach in a wave tank experiment was reported by Petrov (1989), but no explanation of the process was given. Our concept of the mechanism of armor development on beaches, based on White and Day's (1982) discussion on river gravel bars as well as our own observations on gravel beaches, is illustrated in Figure 22. On a beach which typically has constantly changing current velocities, threshold transport conditions for different particle sizes are frequently achieved. Also, smaller particles are shielded by larger particles. These factors combine to allow intermediate-sized particles to be removed and a coarse armor to develop over the finer particles, as shown in Figure 22. Once armoring is achieved on gravel bars in rivers, a process known as structural strengthening occurs (White and Day, 1982), such that a stronger current is required to transport the material available (at least one fourth greater). We assume the same type of structural strengthening occurs on armored beaches.

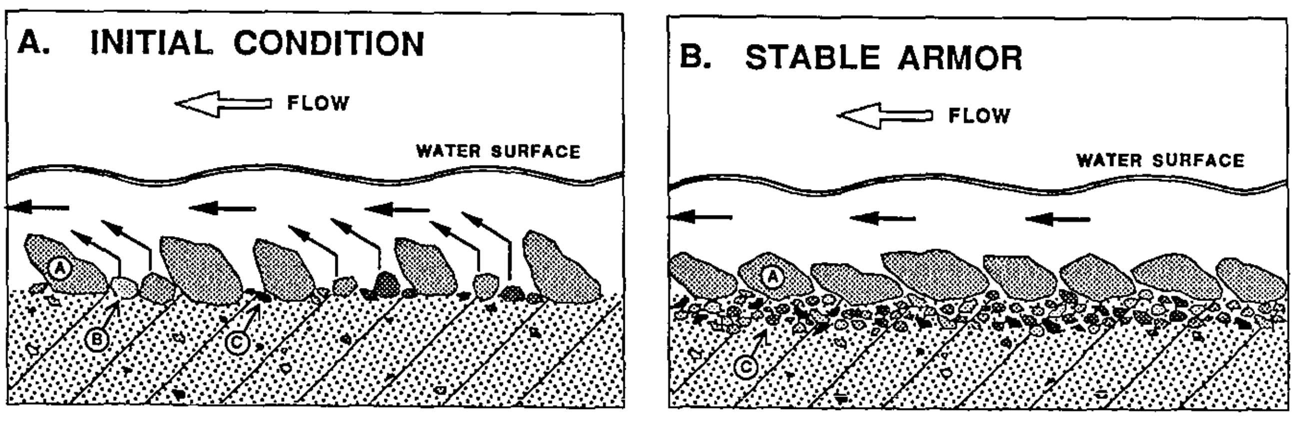


FIGURE 22. Process involved in the development of an armored surface of coarse material on a gravel beach. The particles of size A are too large to be removed by prevailing currents, those of size B are readily transportable, and those of size C are sheltered by the larger particles and are not picked up by the current. The C particles are on the order of 1.5 to 5 times smaller than the A particles.

Many of the gravel beaches in Alaska are armored, especially in their middle and lower sections. This is particularly evident at the EXXON VALDEZ oil spill site. Oil located beneath an armored surface would tend to remain for a longer period of time than subsurface oil on an unarmored beach with similar grain size and wave conditions because of the higher velocities required to remove the armor. Therefore, this is an important aspect of gravel beaches to take into account while applying certain cleanup methods, such as berm relocation, gravel washing, or water flushing.

FEATURES OF GRAVEL BEACHES THAT ENHANCE OIL ACCUMULATION

There are a number of special features of gravel beaches that enhance oil accumulation and preservation during an oil spill. The major ones are:

1) High porosity and permeability that allow penetration from the surface. The open framework of gravel and mixed sand and gravel beaches allows rapid penetration of oil from the surface. Depths of penetration measured in 10's of centimeters has been observed at the spill sites of the METULA (1974), AMOCO CADIZ (1978), and EXXON VALDEZ (Hayes and Gundlach, 1975; Gundlach et al., 1977; Gundlach et al., 1981; Michel et al., 1990).

2) Potential for burial by accretional features. Gravel tends to be highly mobilized during peak and waning stages of storm activity. The finer components of the gravel suite, granule, pebbles and fine cobbles, are also moved readily by normal waves. The gravel may be moved either perpendicular to the beach, in the form of berms or swash bars (Figs. 20 and 21), or parallel with the beach, in the form of rhythmic topography (Fig. 20). The authors observed oil lenses buried to depths of 50 cm under clean gravel berms at segment US-5 on the Barren Islands.

3) Formation of asphalt pavements in sheltered areas. Shorelines with gravel beaches tend to be irregular in outline, and sheltering from wave action is common in numerous localities. Tombolos, depositional spit-like features that occur in the lee of offshore obstructions, are particularly prone to oil accumulation. Likewise, the cresent-shaped beaches that develop downdrift from protruding headlands on coasts with dominant obliquely approaching waves (known as crenulate bays), are areas where oil tends to accumulate, form asphalt pavements, and be buried. The spring 1990 SSAT survey showed that

tombolos and crenulate bays are especially important in the shielding and preservation of both asphalt pavements and buried oil.

DISCUSSION

The EXXON VALDEZ oil spill, more than any other, has stressed the importance of attaining a better understanding of gravel beaches in order to properly treat them at future spills. Gravel beaches show a wide range of morphological and sedimentological behavior, depending upon such variables as general tectonic setting, local tectonic history, exposure to waves, local sediment sources, and internal character of the local waves. Specific problems, such as armoring of wave-cut platforms and low-tide terraces, are virtually unstudied and poorly understood. Projections of how quickly gravel beaches will recover to normal configurations in response to cleanup methods, such as berm relocation and gravel washing and replacement, requires the coastal geologist to call upon studies done on rivers and sand beaches for answers. Research, such as sediment transport studies on a variety of natural gravel beaches, seasonal monitoring of changes in gravel beach morphology at both sheltered and exposed localities, and continued long-term studies of oiled gravel beaches at oil spill sites such as the EXXON VALDEZ, should be initiated to alleviate this problem. The results reported below on our studies at the EXXON VALDEZ site, as well as results from the studies by Exxon and its consultants and the State of Alaska, hopefully will provide a foundation for future research on this difficult problem.

RESULTS OF STUDIES IN PRINCE WILLIAM SOUND

INTRODUCTION

The PWS shoreline is not an exposed, open ocean shoreline as are normally described in textbooks—the shorelines of southern California, outer Cape Cod, and the Outer Banks of North Carolina being prime examples. Instead, it is a highly sheltered, deep water shore of a glaciated mountain range flooded relatively recently as a result of the retreat of the glaciers and sea-level rise. Though the winds are strong in the area, fetch is limited and wind directions fluctuate such that wave energy is dissipated along the shoreline in brief spurts separated by long periods of relative calm. No major rivers empty into the Sound, thus sediment supply from land is restricted to the mouths of the numerous streams of the region and the termini of glaciers. Therefore, sediments are generally in short supply and erosional or neutral shorelines predominate. Another complication is the fact that most of the PWS beaches have not yet achieved the erosional/depositional pattern that existed before the 1964 "Good Friday" earthquake. They are, thus, out of equilibrium with respect to pre-earthquake conditions.

Because of these uncertainties, it was not possible to predict the rate of natural removal of oil from the shoreline in PWS. It was anticipated that exposed rocky shores could be cleaned very quickly, and this was the case. The big uncertainty was in two areas: coarse beaches where the oil had penetrated deep into the sediments and sheltered shorelines, particularly those that have highly irregular surfaces.

Owing to logistical limitations, all of the possible shoreline types in PWS which were oiled during the spill were not included in the 18 original survey sites. However, we do feel these stations represent a reasonable sampling of the different possibilities while focusing on the two most problematic types. Furthermore, six stations were added in the summer of 1990 to augment both the geological and biological studies.

The 18 permanent stations are located on six different shoreline types, which are listed below in general order of decreasing potential hydrodynamic energy (for the stations studied):

Type	Stations
Cobble/boulder platforms with berms	N-1, N-3, N-4, N-7, N-15, N-17
Raised rocky platforms with minimal sediment	N-2
Bayhead beaches	N-14, N-18
Pebble beaches with tidal flats	N-8, N-9, N-11
Rocky rubble slopes with raised bay bottoms	N-5, N-12, N-13
Sheltered rocky coasts	N-6, N-10, N-16

Tables 3 and 4 give the locations, degree of exposure, amount of initial oiling, type of treatment, and dates of surveys for each station. The stations are located on Figure 16. The survey results are discussed below by shoreline type, with a general discussion of each type followed by detailed discussion of each station in that type.

COBBLE/BOULDER PLATFORMS WITH BERMS

General Description of Shoreline Type

These features are the closest approximation to exposed gravel beaches that occur within the oiled portion of PWS. They are not depositional throughout the intertidal zone, the only purely depositional components being storm and lower-level berms perched near the high-tide line. The middle and lower portions of the profiles are typically gently sloping surfaces of bedrock covered by a veneer of gravel. The origin of these rock platforms within PWS, many of which were raised (or lowered) by the 1964 earthquake, is something of a mystery.

These relatively flat, erosional rock benches, which occur within the intertidal zone of areas exposed to significant wave action, are typically referred to as shore platforms. In a summary of the literature on the origin of shore platforms, Carter (1988) notes with surprise that processes other than wave action, such as biological, chemical, or freeze/thaw action, have most often been credited with being responsible for their origin. He notes further (p. 147) that "rates of downwear are relatively fast" (measured in cm/yr) and many platforms "may be quite recent in origin". Though we have conducted no original research on this topic in PWS, the direct correlation of shore platform development with exposure to wave action throughout PWS leads us to believe that they are formed primarily by wave abrasion. Ice scour may augment the process in places. Shore platforms in PWS are more subtle, narrower, and more steeply dipping than those found along the exposed outer coast of the Gulf of Alaska. The smaller waves in PWS and recent tectonic readjustments there probably account for these differences.

The wide, flat middle and lower portions of the stations we call cobble/boulder platforms with berms are, thus, for the most part, shore platforms with a veneer of mobile gravel, some of which is eventually deposited into berms at the landward end of the platform. The flat profile and the relatively low penetration of backwash water volume means that the gravel clasts are moved back and forth in a horizontal sense and that wave energy is dissipated over a wide area. Oil penetration, which may reach significant depths in the berms, is restricted by the rock platform in the middle and lower reaches of the profile. Hydraulic flushing is also enhanced in those parts of the profile, because the bedrock platform forces wave backwash to be quickly discharged to the surface.

Station N-1

Introduction. This station is located at Pt. Helen on the southeast corner of Knight Island, one of the more exposed sites in PWS. Consequently, the station contains abundant coarse material—pebbles, cobbles, and boulders—that show signs of frequent transport by wave-generated currents (i.e., rounding and sorting). This beach is exposed to the east, the direction from which the dominant winds blew during storms in the fall-winter-spring period of 1989-90. The effective fetch distance ranges from 15-20 km in a due easterly direction, up to 45-50 km to the north-northeast. No seasonal measurements of wave or current data are available for this or any of the other NOAA monitoring stations. Due to uplift in the area on the order of 2.5 m during the 1964 earthquake, the beach has not completely readjusted to pre-earthquake conditions. A field sketch, beach profile, and sediment distribution plot for the profile on 24 May 1990 are given in Figure 23 and selected photographs are presented in Figures 24 and 25.

N-1 24 May 90
Point Helen

A.

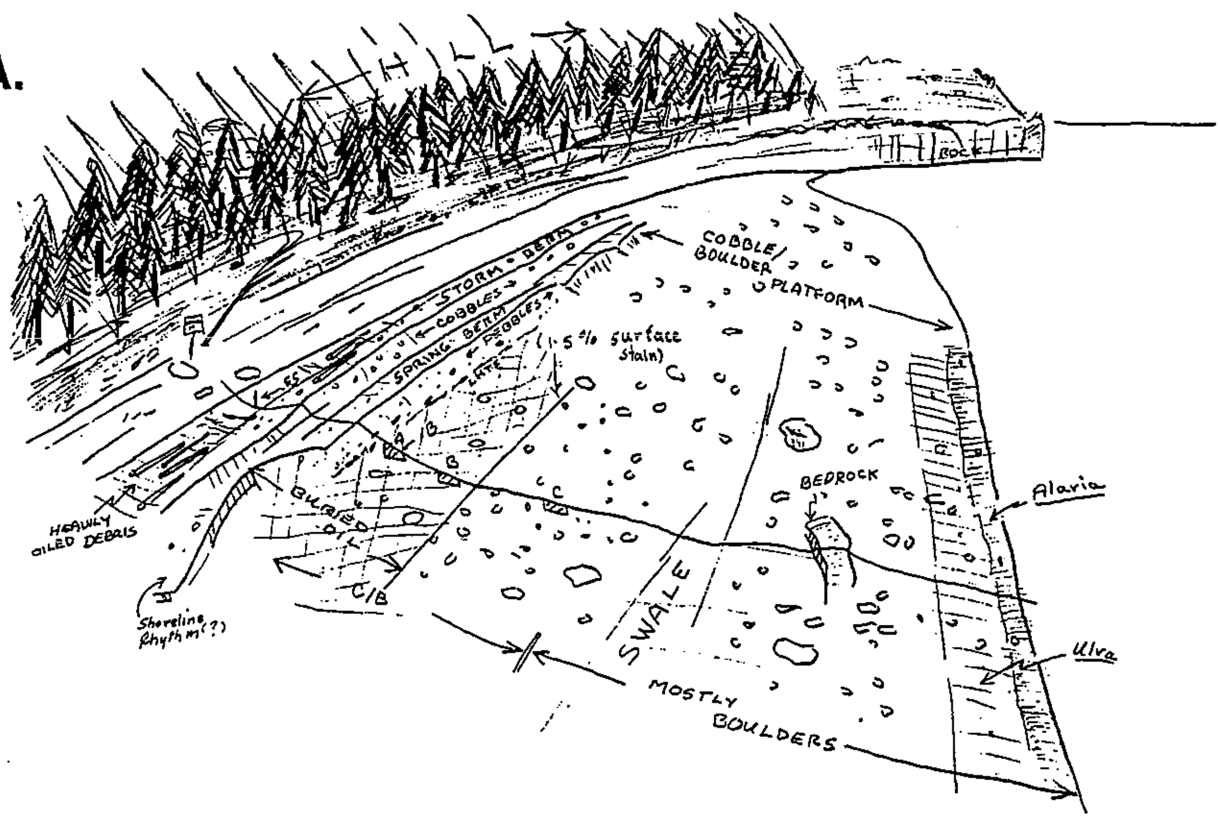


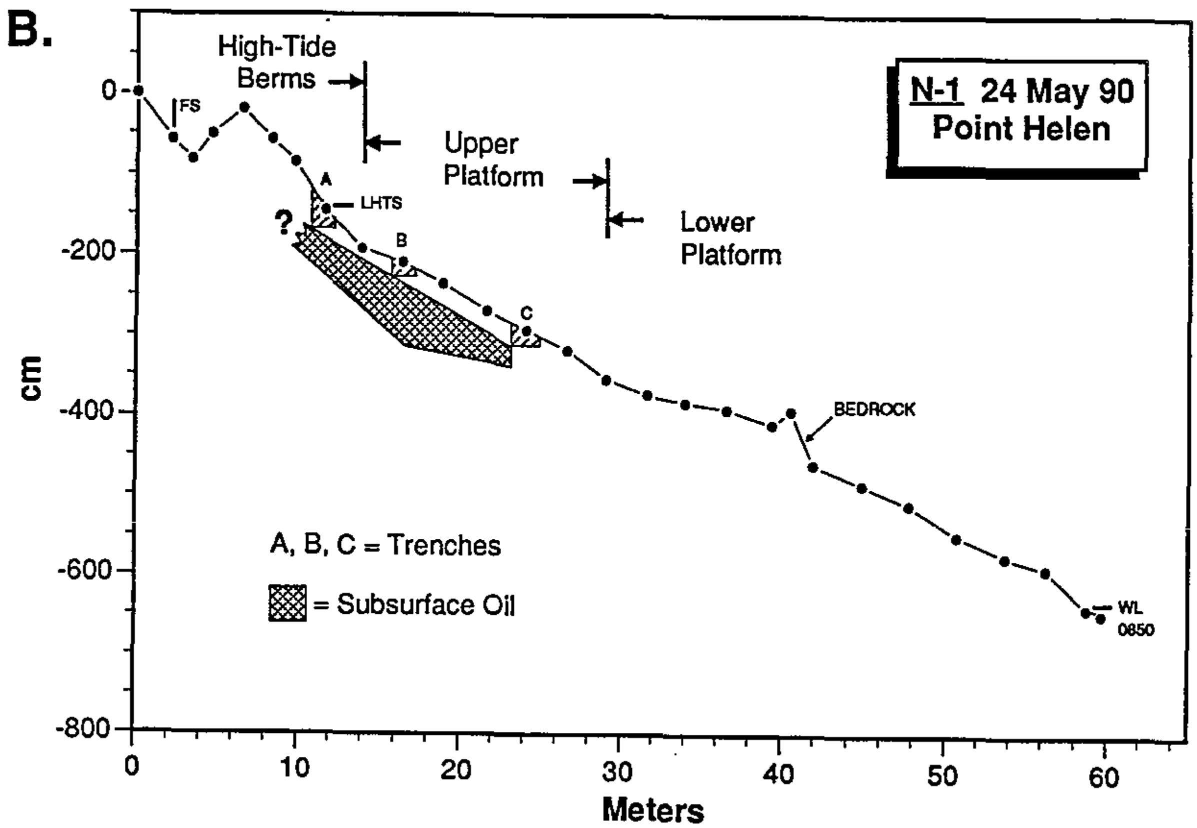
FIGURE 23. Station N-1 at Point Helen, Knight Island, on 24 May 1990.

A. Field sketch showing general morphology, sediment distribution, and oiling in the vicinity of the N-1 profile. Note zone of buried oil and presence of heavily oiled debris at the storm high-tide line.

B. Profile N-1 plotted at 5:1 vertical exaggeration. Note increase in slope in landward direction. The profile is divided into three morphological zones—lower platform, upper platform, and high-tide berms. The buried oil extended for a width of 15 m and averaged 30 cm at either end with a maximum thickness of 50 cm. Note that sediment reworking has removed much of the oil from the upper ± 30 cm.

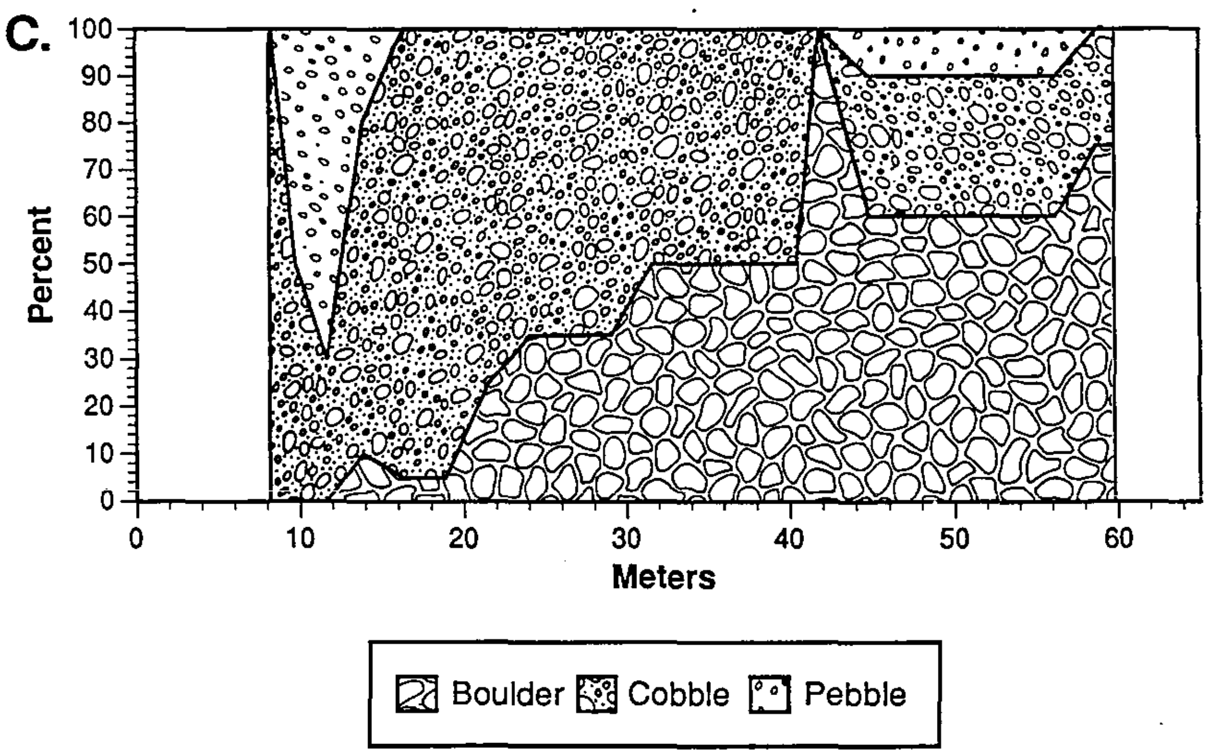
C. Distribution of surface sediments along profile. Note general increase in clast size in seaward direction, with pebbles being most abundant on the high-tide berms and boulders composing more than 50 percent of the surface sediments on the lower half of the profile.

B.



High-Tide Berms
Upper Platform
Lower Platform
N-1 24 May 90
Point Helen
FS
A
LHTS
?
B
C
BEDROCK
WL
0850
A, B, C = Trenches
= Subsurface Oil
cm
0
-200
-400
-600
-800
0
10
20
30
40
50
60
Meters

C.



Percent
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Meters
Boulder
Cobble
Pebble

Oiling and Treatment History. Pt. Helen was one of the most heavily oiled shorelines in PWS. Because of concerns that oil would be remobilized during any treatment in 1989 and impact the terminal fishing at the hatchery in Sawmill Bay, all cleanup activities at Pt. Helen were delayed until the very end of the 1989 period. Thus, during about the first week or two in September, Pt. Helen was the target of intensive hot-water washing with both maxibarges and omnibooms for a very short period late in 1989. After washing, the entire stretch was treated with Inipol and Customblen. In 1990, we have no records of any treatment conducted at this site; we saw no evidence of Customblen in any of the trenches dug in May or September 1990.

Morphology and Beach Dynamics. There are three morphologically distinct components of this profile:

1) High-tide berms

   The upper $\pm$14 m of the profile is made up of a primary storm berm, which had a series of lower-level berms on its beachface between September 1989 and May 1990, as can be seen on the profile overlay plots in Figure 26. The average slope of the beachface is 15°. These types of high-tide berms are common features on gravel beaches throughout the world.

2) Upper platform

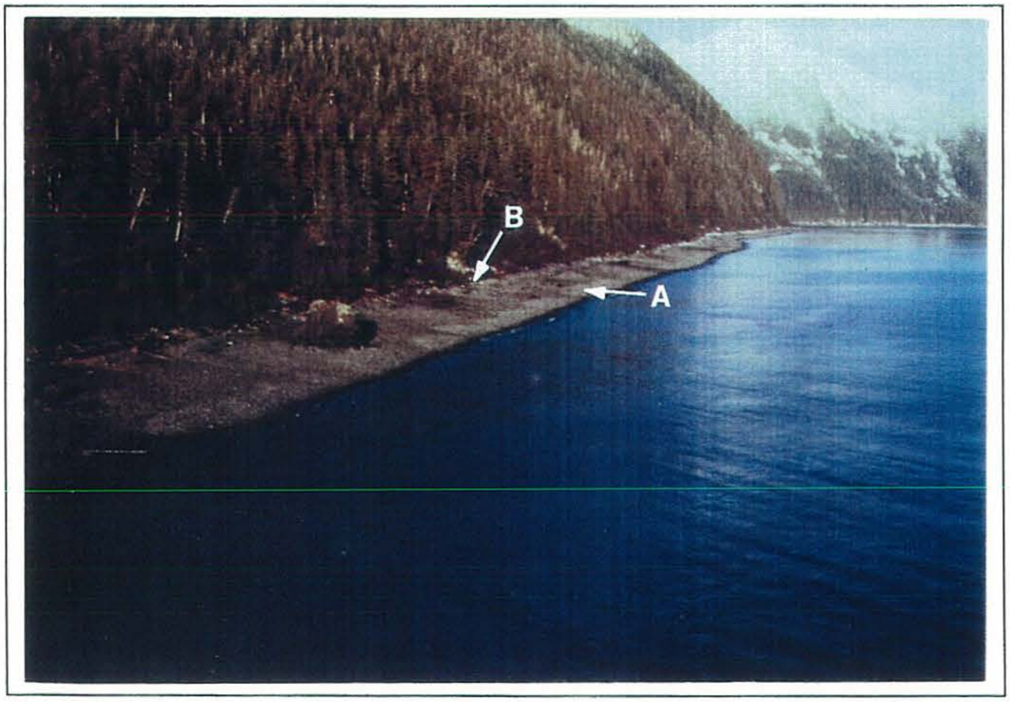
   A cobble to boulder-sized armor has formed over the surface of this central (14-28 m) portion of the profile, which showed little change between September 1989 and September 1990. The ratio of boulders to cobbles increases in a seaward direction. This part of the profile, which slopes offshore at an angle of 6°, is thought to be an uplifted, wave-carved bedrock surface.

FIGURE 24. (Facing Page) Photos of station N-1.

A. Pt. Helen at low tide on 5 January 1990. Note presence of gravel swash bars (arrow A) in the intertidal zone that were obviously migrating in a southerly direction. Arrow B points to location of station N-1. Raised shore platform is clearly visible in this view. Photo by D. Hall.

B. Northerly view from top of storm berm on 20 October 1989. Person is standing on profile line. The storm berm had been overtopped and eroded within last few high tides, and oiled debris (arrow) was washed over the top of the berm. Photo by D. Hall.

A.



B.

3) Lower platform

This zone, which extends from 28 m to the low spring tide line (±60 m), periodically contains asymmetric bars built by wave action called swash bars (Fig. 26). The surface of the lower platform, which contains several major protruding rock outcrops, slopes offshore at an angle of 6°. The surface material, which is covered by heavy algal growth (Ulva and Alaria) near the spring low-tide line, is >50 percent boulders. This zone is probably an uplifted wave-cut bench (shore platform) in the making.

The beach profile at station N-1 was surveyed seven times (see Table 4). Careful examination of the data reveals a few obvious discrepancies in the readings, probably because the profiles were not always run along the same line (a front stake was not established until the May survey). It is clear from the data, however, that this was one of the most dynamic of the beach stations surveyed within PWS. In their report to NOAA on the fall and winter surveys, Sexton, Gibeaut, and Balcom (1990) state that the storm berm "retreated landward" 2-3 m between the 16 September 1989 and 20 October 1989 surveys. Such motion might have occurred, but we are sure the two profiles were not run along the same line, thus the amount of motion is unclear. There is evidence that the storm berm was overtopped during the interval in question, because significant amounts of oiled debris were transported over the storm berm to the previously "clean" back berm area (Fig. 24B). None of the later surveys showed any motion of the storm berm.

A major change in the morphology of the beach took place between the 6 November and 7 December 1989 surveys. The profile was rather featureless on 6 November, except for the smooth-faced storm berm. In the field notes of 7 December, however, Michel notes that "the shoreline is very irregular with angled gravel bars indicating transport to the south". As can be seen in Figure 26A, the profile measured on that date crossed two of the bars, a large swash bar near low water and an obliquely welded cobble bar higher on the profile, 1.3 m below the top of the storm berm. The aerial photograph in Figure 24A shows that swash bars were still present on the profile on 5 January 1990. The lower swash bar remained in the same position (Fig. 26B), whereas the sediments of the upper bar were molded into a spring-tide berm and moved higher on the profile. In the field notes of 5 January, Gibeaut observed that "swash bars form low angle to shoreline and open to the south". The profile measured on 1 February 1990 was quite similar to the 5 January profile; however, by 24 May 1990, there was no trace of any swash bars on the beach (Fig. 23). No significant morphological changes occurred on this beach during the summer of 1990, as verified by the survey conducted on 6 September 1990.

The concepts of the potential for the sediment on a beach to be mobilized and the thickness of sediment envelope that develops are important considerations for oiled beaches. Though the sediment at station N-1 is coarse (>50 percent cobbles and boulders), it was obviously mobilized frequently during the non-summer months of 1989-90, as evidenced by the presence of mobile berms and swash bars on the profile (Figs. 24A and 26). The thickness of the vertical sediment envelope was rather small, however, being restricted primarily to the heights of the swash bars (30-40 cm) and the spring-tide berms (50-60 cm). The storm berm was never completely remobilized. Another limiting factor to sediment envelope development was the occurrence of a veneer of cobble/boulder armor over much of the rock platform, which means a higher-than-normal current velocity is required to set the sediments into motion.

<u>Sediments</u>. The pebbles, cobbles, and boulders of Pt. Helen are no doubt derived locally, probably from outcrops exposed along the shoreline to the north. They are quite hard and do not crumble readily. The composition of the clasts is variable, with the following possibilities (in decreasing order of abundance):

1) Slightly metamorphosed deep-water sandstones.

2) Dark gray-black or reddish-brown <u>hard</u> siltstone and argillite.

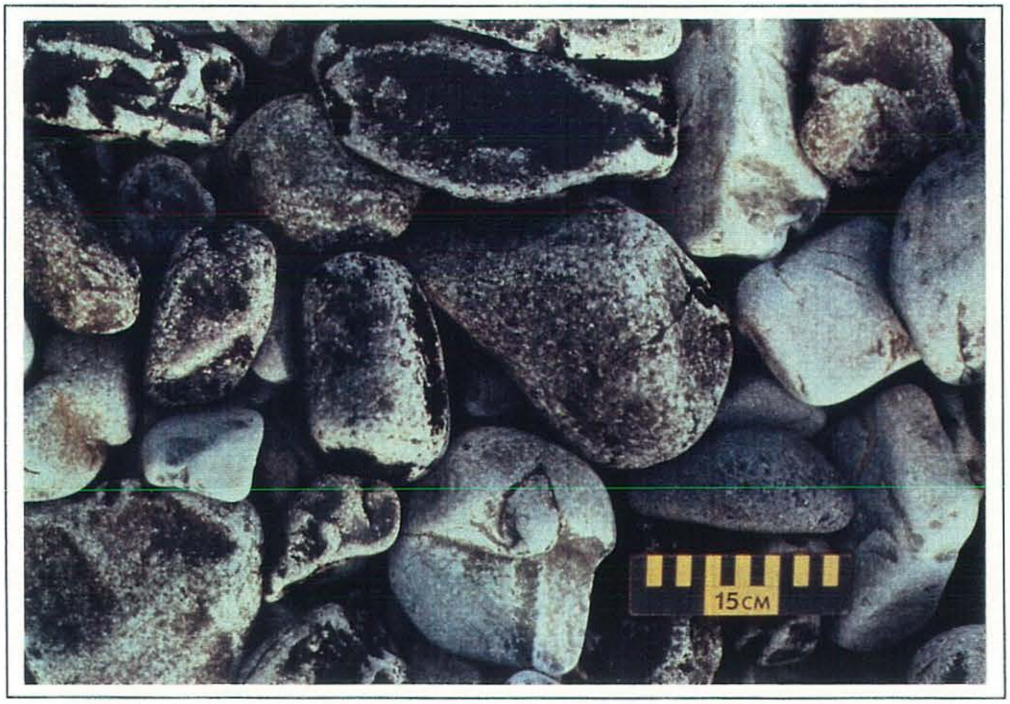
3) Miscellaneous basaltic lava, metamorphosed conglomerate, and others.

FIGURE 25. (Facing Page) Additional photos of station N-1.

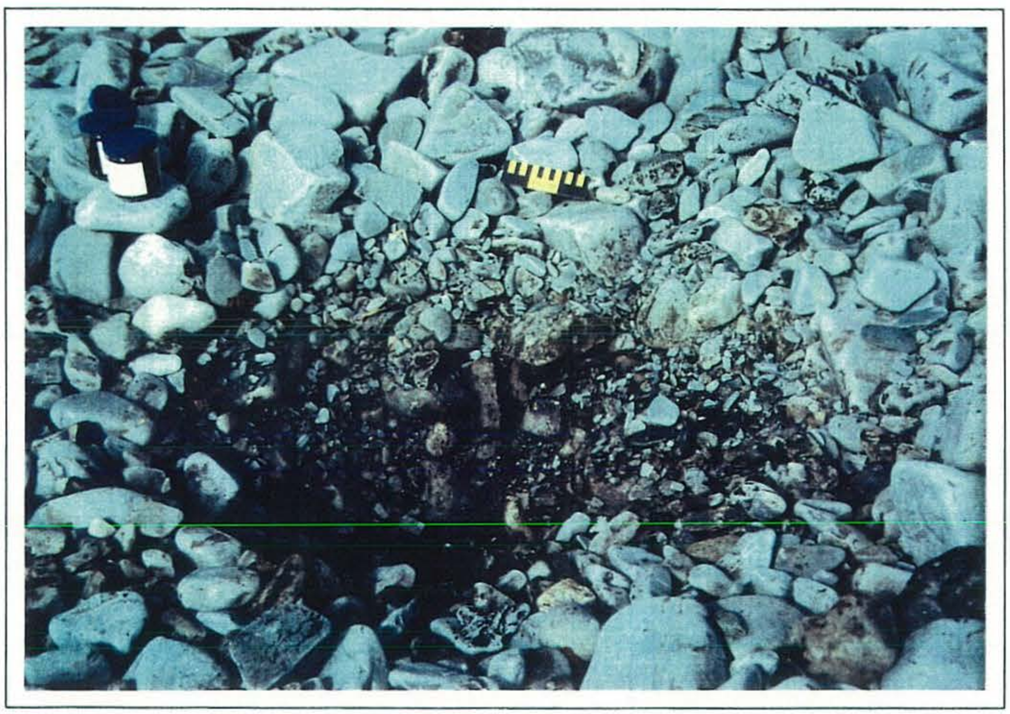
A. Oil remaining on cobbles and small boulders on the surface of the upper platform on 20 October 1989. Also note rounding and moderate sorting of the gravel, which has a slight tendency toward a rod-like shape. Photo by D. Hall.

B. Trench A on 24 May 1990 (see Fig. 23B for location and Fig. 29 for description of trench). Note relatively clean surface and increase in oiling with depth. The subsurface sediments, though coarse, are very poorly sorted. Photo by D. Noe.

A.



B.



Our field team measured the detailed distribution of clast size along profile N-1, which is representative of the entire Pt. Helen area, on 24 May 1990. Careful estimates were made of relative abundance of clast type—pebbles (P), cobbles (C), boulders (B), and granule/sand (Gr/S)—at 25 intervals along the profile. The results of these estimates, which are given in Figure 23C, show that: 1) the amount of pebbles is greatest on the high-tide berms; 2) cobbles predominate the upper platform, with the percentage of boulders increasing in a seaward direction; and 3) boulders make up >50 percent of the surface of the lower platform, with an increase in pebbles and cobbles near the lower portion. This distribution pattern is a result of the fact that the middle part of the profile, the zone subjected to the longest period of intense wave and wave-generated current action during the elevated portions of the tidal cycle, has been subjected to structural strengthening. It is this middle part of the profile where the maximum downthrust of plunging waves is felt. Hence, a well-developed armor of cobbles and boulders has developed there. During periods of intense sediment transport, the pebbles and finer cobbles bypass over the surface of the central portion of the profile to be deposited at the landward or seaward ends.

Detailed studies of clast texture were carried out at 6 sites along the profile on 23 June 1990. At each site, twenty clasts were randomly sampled by laying a profile rod perpendicular to the profile line and measuring the first 20 clasts intersected by the rod. For each clast, the following were determined: (1) composition; (2) roundness, using the roundness chart given in Figure 19; and (3) the length of the long (L), intermediate (I), and short (S) axes of the clast. The mean size of each clast was approximated by means of two calculations: (1) (L+I+S)/3, which is a fair representation of the true volume of the clast; and (2) (L+I)/2, which is an approximation of the maximum projection area of the clast, an important parameter related to transport by moving water, and also a close representation of the size chosen by the observer in the field when estimating surface sediment size by comparison with the chart shown in Figure 18. A plot of (L+I)/2 for each clast at the 6 stations versus distance along the profile is given in Figure 27. This is a more precise representation of the offshore-coarsening trend shown in Figure 23D. Comparisons of mean clast size (L+I+S)/3 of the surface armor with that of the underlying layer was made at two stations, number 3 (10 m from front stake) and number 4 (20 m from front stake), with the following results:

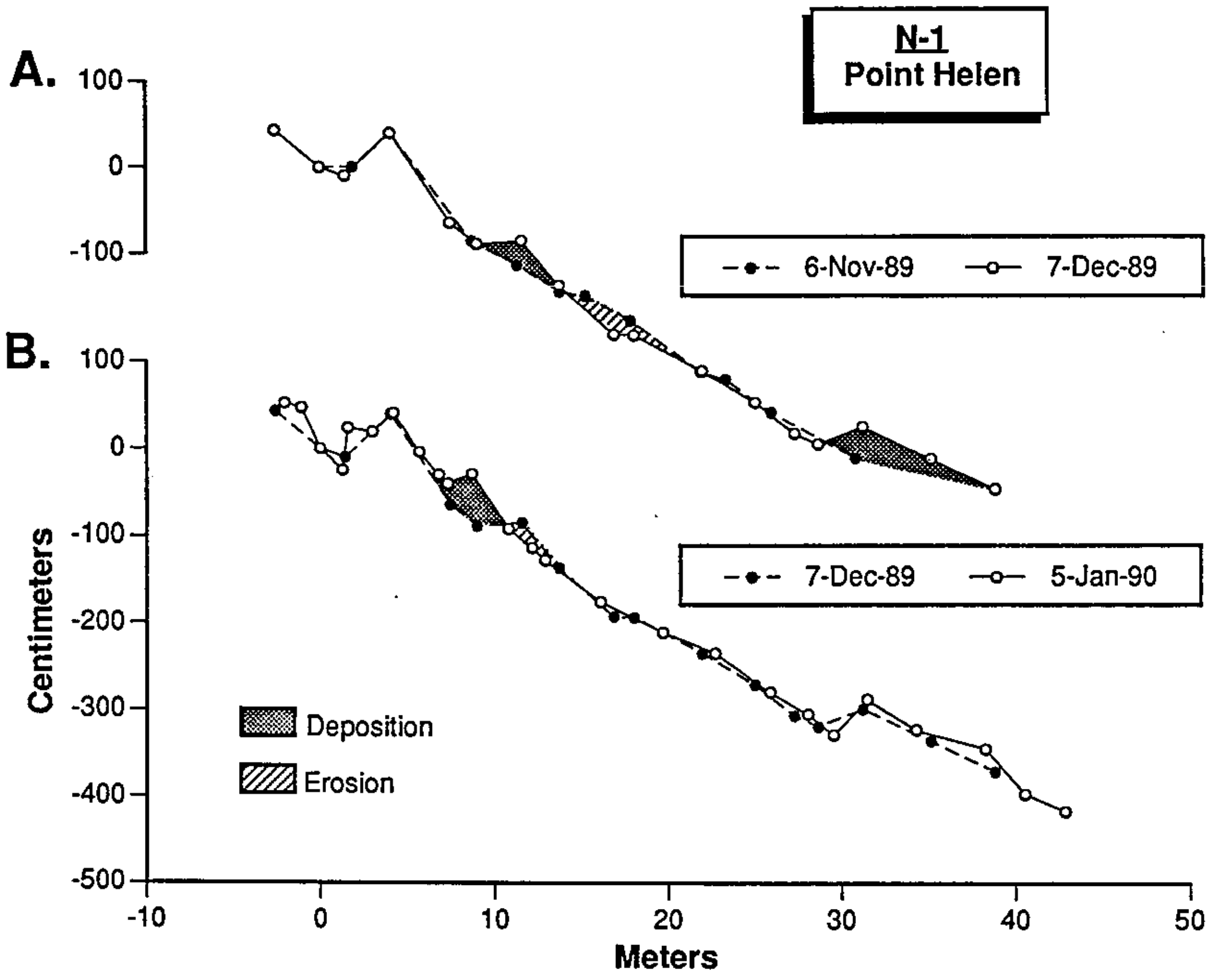


FIGURE 26. Changes in the configuration of the beach at station N-1 between 6 November 1989 and 5 January 1990.

A. Two bars developed on the profile between 6 November and 7 December 1989, a large swash bar near low water and an obliquely oriented cobble bar at 1.3 m below the crest of the storm berm.

B. The sediments in the cobble bar were moved higher on the profile and molded into a spring-tide berm between 7 December 1989 and 5 January 1990. The swash bar located lower on the profile showed little change. Also note the lack of change along the upper platform (middle) portion of the profile.

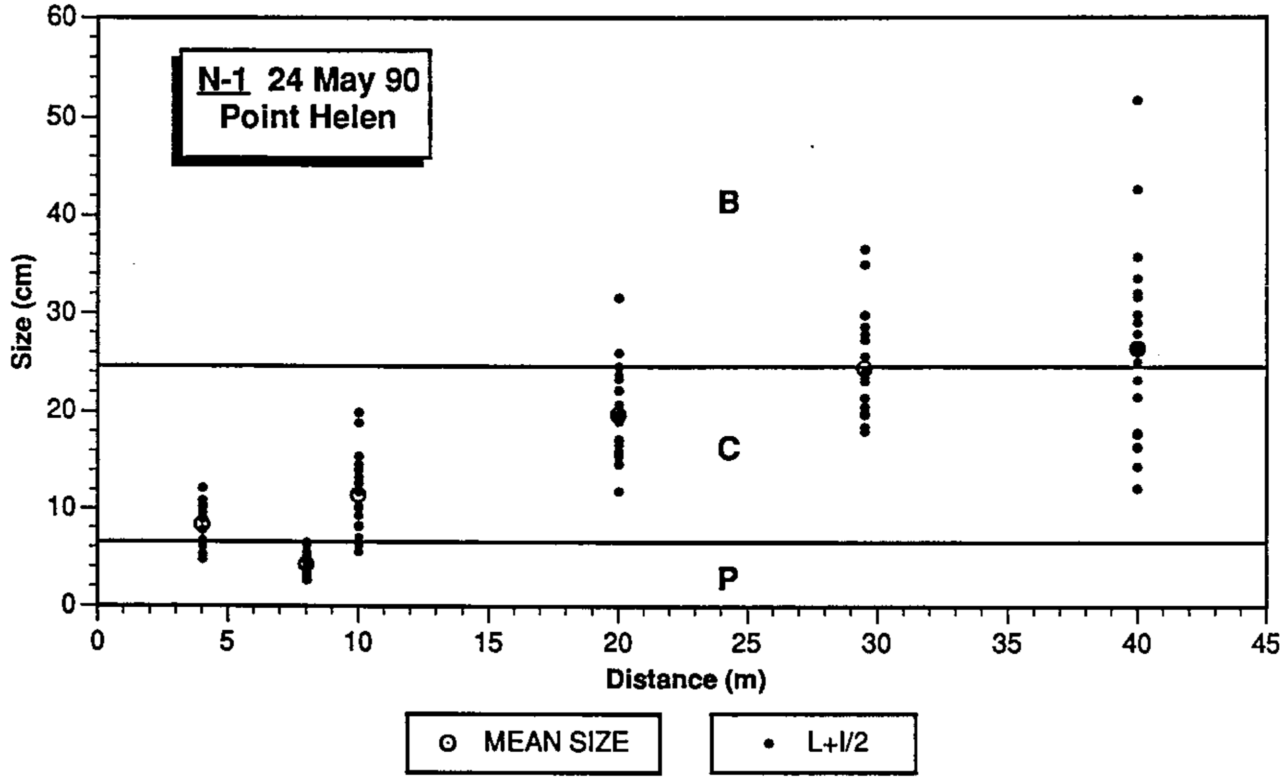


FIGURE 27. Size (L+I/2) of clasts occurring on the surface along profile N-1 on 23 June 1990. Cobbles and boulders dominate the lower portion of the profile. This offshore-coarsening trend is typical of all the sites we classify as <u>cobble/boulder platforms with berms</u>.

	station 3	station 4
armor	9.5 cm	16.5 cm
underlying layer	1.5 cm	4.3 cm

The roundness of the clasts is an important aspect of gravel beach sediment that is helpful in making estimates of how long oil is apt to remain on the beach. Rounded clasts on the beach means that they are moved frequently by wave action, whereas angular clasts indicate little or sporadic transport. To amplify this point, a plot of roundness versus length of long axis for all the measurements made at station N-1 are compared with those made at station N-5, a sheltered rubble slope, in Figure 28. All of the clasts measured at station N-1 were either subround or round, with a slight tendency of the pebbles and cobbles on the berms to be better rounded than the boulders on the armored platforms. The photograph in Figure 25A illustrates the roundness of the gravel at station N-1. The clasts at the sheltered station, N-5, were angular and subangular.

Over the fall and winter monitoring period, fourteen trenches were dug and described on this profile. The three that were dug on 24 May 1990 are illustrated in Figure 29. These descriptions show that, in every case, coarse material overlies fine material at depth, verifying comments made earlier concerning the development of a surface armor along this profile. For example, a trench 70 cm deep was dug near the middle of the upper platform in September 1990, which contained 10 percent boulders, 80 percent cobbles, and 10 percent pebbles in the upper 22 cm and 10 percent boulders, 10 percent cobbles, 30 percent pebbles, 30 percent granules, and 10 percent sand in the lower 26 cm. The lower unit contains more finer material (granule and sand) on the lower portions of the profile (Fig. 29), possibly as a result of the uplift bringing into the intertidal zone fine-grained offshore sediments that have since been sheltered from erosion by the surface armor.

Oil Distribution Patterns. The distribution of surface oil (based on visual estimates made in the field) over time is shown in Figure 30. Figure 30A shows the percent coverage at each interval along the profile for selected months, whereas Figure 30B shows the percent surface coverage integrated over the entire profile for each month. This same format is used for all profiles described in this report.

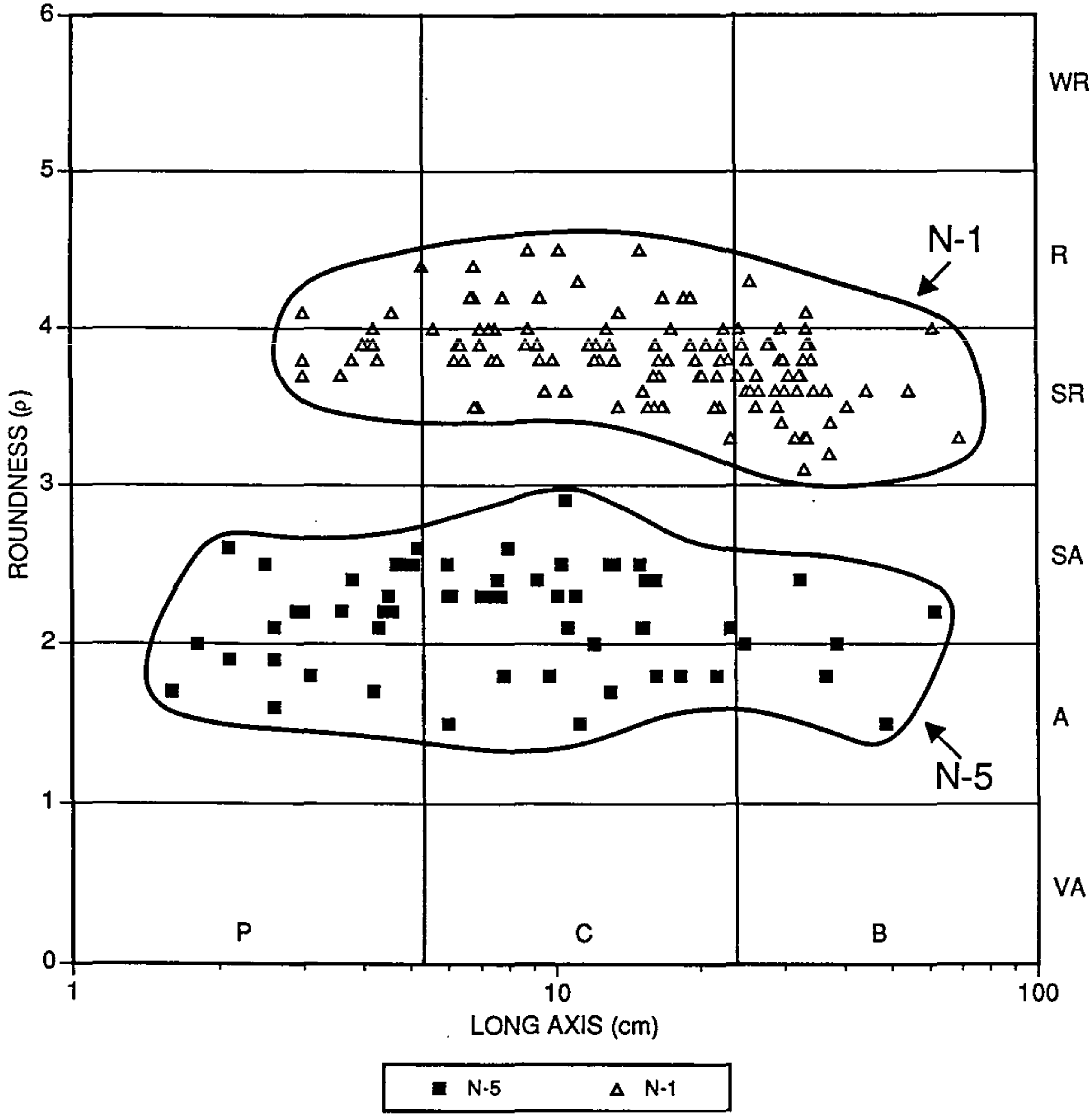


FIGURE 28. Roundness of surface clasts measured at 6 stations on profile N-1 and 3 stations on profile N-5. The gravel on the more exposed station (N-1) is much better rounded. See roundness chart in Figure 19 for comparison. The roundness (ρ) scale was proposed by Folk (1955).

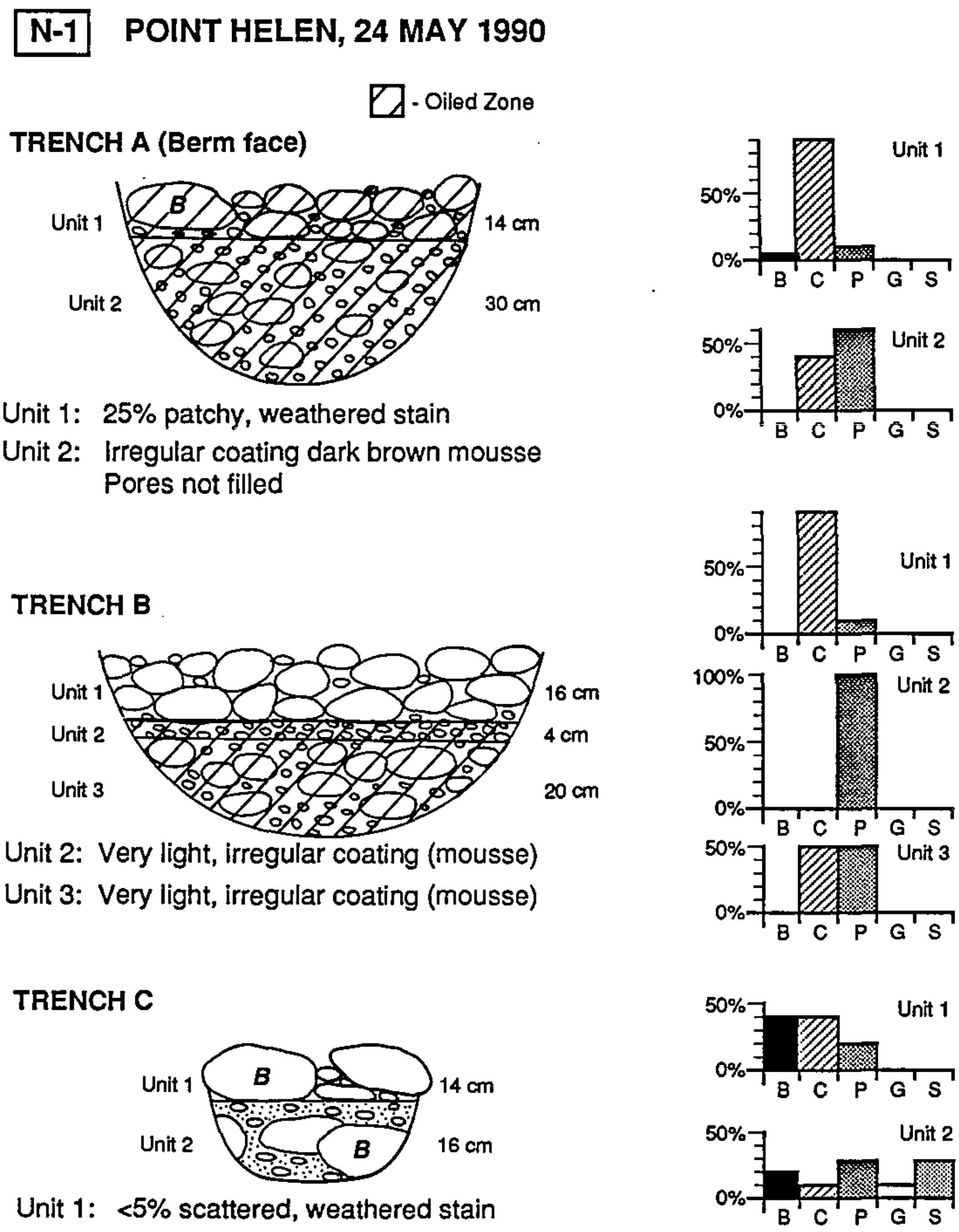


FIGURE 29. Description of trenches dug on 24 May 1990 at station N-1 (see Fig. 23B for location). Note tendency for upper units to be somewhat coarser-grained than lower units. Also note that the upper sediments in trenches A and B are relatively free of oil as a result of wave action during the nonsummer months of 1989 and 1990.

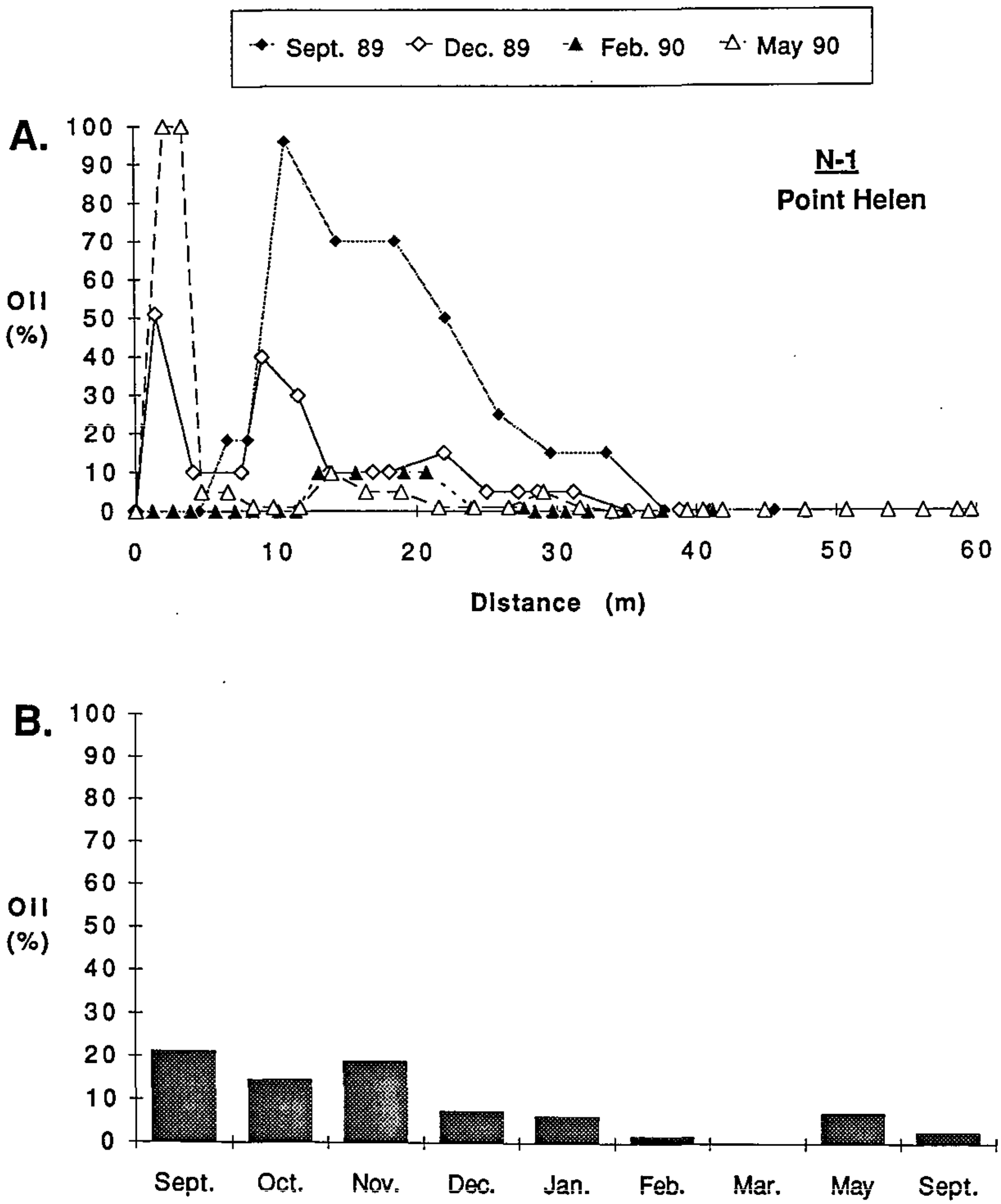


FIGURE 30. Surface oil plots for N-1, Pt. Helen.

A. Plots of the percent coverage of surface oil (visual estimate made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

There were several distinct patterns in the distribution of surface oil contamination at Pt. Helen. In September 1989, there was no oil behind the storm berm, the heaviest oiling being at the high-tide line, and oil covered (visually) the upper two-thirds of the intertidal zone. After the first big storm in mid-October, oily debris was pushed over and behind the storm berm and under log piles (Fig. 24B), where it remained.

Surface oil on the beachface steadily declined until only a trace of stain remained at the upper intertidal zone as of September 1990. The sediment chemistry results showed the same trend (upper part of Table 6), with about 95 percent reduction in the oil concentration in surface samples. It should be noted that there will be large variations in the TPH of sediments because of the large differences in grain size and the heterogeneity of the oil distribution along the profile. Even so, the samples show that most of the surface sediments in the intertidal zone were cleaned very quickly; most of the remaining oil was on the larger clasts (Fig. 25A), even though they, too, eventually were cleaned.

The distribution of subsurface oil was quite different. First of all, there is even larger variability. Also, because the depth of sampling varied widely over time, the trends are more difficult to portray. To facilitate comparison of results, the sediment TPH data have been divided into two depth classes, less than 25 cm and greater than 25 cm (Table 6). The break at 25 cm was selected because it appeared to be the depth to which surface sediments were regularly mobilized on this shoreline type. Many of the >25 cm depth samples listed in Table 6 were collected from depths of 45-50 cm, usually at the bottom of the trench.

TPH concentrations at the high-tide berms ranged from 400 to 5680 ppm. Only the samples from <25 cm depth showed a decreasing trend, from 3,750 to about 1,000 ppm, as expected from visual observations. Along the upper platform, TPH in the deeper samples varied by a factor of 35, even between January and February 1990, though the shallow samples were much lower and more consistent. Samples from the lower platform were mostly less than 25 cm in depth, and the results were mostly in the 100-200 ppm range. It appears that washing of this shoreline did not result in large-scale transport of oiled sediments into the lower intertidal zone, presumably because of the very coarse sediments and stable armor.

TABLE 6. Sediment TPH (in ppm) for Pt. Helen (N-1) by morphological zone.

Surface Samples

Date	High-Tide Berms	Upper Platform	Lower Platform	Mean
9/89	1,420	860	840/390	880
10/89	60	140	40	
11/89	80	180	130	130
12/89	270	250		260
1/90	100	40		70
2/90	<10			

Subsurface Samples

Date	High-Tide Berms		Upper Platform		Lower Platform
	< 25 cm	> 25 cm	< 25 cm	> 25 cm	
9/89	3,570	1,970		6,760	180
10/89		2,810			
11/89		5,680		980	119
12/89	1,000	5,370	740		
1/90	1,060	400	420	5,330	1,090
2/90		4,850/2,700		220	160
9/90		1,710		7,590	

It is important to note that the data in Table 6 are for samples taken at the base of the active high-tide berms; the sediments in the berms themselves were very clean after September 1989, down to depths of about 1 meter. Thus, on Figure 23A, a question mark is used to indicate uncertainty in the landward extent of the oil under these berms. It was difficult to dig trenches in these berms because the sediments were so loosely packed. The subsurface oil tended to persist over the winter at the base of the berms as well as in the stable upper platform (Figs. 25A and 29).

Based on visual observations in the trenches, there appeared to be a steady decrease in oil at depth over time. By September 1990, the upper 15-20 cm appeared clean throughout the intertidal zone; minor oil droplets and very light sheen were observed at depth. The heaviest oil remaining at this location was above the high-tide zone, where oil remained under the logs behind the storm berm. Between the storm and high-tide berms, 80 percent of the cobbles and pebbles were oil-stained at 20-40 cm depth, although there was no free oil in the trench. The most heavily oiled sediments observed in September 1990 were exposed at the base of the storm berm in a small scarp about 50 m south of the profile.

It appeared that much of the heavy subsurface oil observed in late winter had been significantly reduced by September 1990. The remaining oil had two distributions: 1) as coating, stain, sheen, and droplets on individual clasts in the intertidal zone, and 2) as heavily oiled debris and particles of oil-saturated sediments in the storm-berm area. The relatively rapid reduction of subsurface oil from the upper intertidal zone is likely attributed to reworking of sediments down to 60 cm in the high-tide berms. The stable upper and lower platform showed little sediment reworking at the depths of the buried oil, yet much of the oil in these zones also decreased during the summer. The presence of the shallow bedrock platform most likely aided flushing of oil from the coarse and highly porous substrate. Even the subsurface sediments of the upper platform lacked any significant fraction of sediments smaller than pebbles. The role played by nutrients is unknown, although this area was treated with nutrients in 1989.

<u>Observations on Biota</u>. The high-tide berms have a depauperate biological community because of sediment mobility and dryness of this zone. The upper platform, though relatively stable, still shows evidence of some sediment movement (roundness of cobbles and boulders); the larger boulders are colonized by limpets, barnacles, and litterine snails. The lowest part of the lower platform is covered by an abundant growth of algae and is very stable. The biota in this zone could be affected by sporadic movement of the lower swash bars which could bury attached organisms with up to 40 cm of gravel. The mid-zone biological survey quadrats are located in a subtle swale in front of, and downdrift from, a berm-like ridge and bedrock outcrop. There is a possibility that ground water seepage from the upper beach drains across this swale.

Station N-3

Introduction. This station is located in a small indentation along the northwest side of Smith Island (Fig. 16). The beach is oriented east-west and is exposed in a due northerly direction. The intertidal zone contains abundant, abraded coarse material, which grades perceptibly from dominant pebbles to dominant boulders in an offshore direction. The effective fetch is around 10-12 km in a northerly direction. A large expanse of open water occurs to the north-northeast of the site, a straight line distance of 45-50 km. This open-water fetch line intersects the beach at a 55° angle. Located 70 km from the epicenter, this station was uplifted 1.5 m during the 1964 earthquake, with a well-defined, vegetated uplifted storm berm being clearly visible behind the present beach (Fig. 31A). A field sketch, beach profile, and sediment distribution plot for the profile on 25 May 1990 are given in Figure 31, and selected photographs are presented in Figures 32 and 33.

Smith Island was very heavily oiled by relatively fresh oil on 26 March 1989, when >70 knot winds first blew the slick ashore. This site caught and held a large amount of oil, and it was a chronic source of sheens throughout 1989 and 1990 (note the sorbent boom deployed in May in Fig. 32A). Cleanup crews worked on this section of Smith Island several times during 1989, using cold, warm, and hot water flushing. Inipol and Customblen were used in both 1989 and 1990. In late August 1990, the berm was relocated and the exposed subsurface sediments treated with Inipol and Customblen; during our survey on 7 September 1990, Inipol was very visible at depths down to 40 cm.

Morphology and Beach Dynamics. As shown in Figures 31A and 31B, the profile is divided in three morphological units:

1) High-tide berms

   A well-defined storm berm, the crest of which did not move during the survey period, is the dominant feature on this part of the profile. Spring-tide berms were usually present on the seaward face of the storm berm. Pebbles and cobbles make up more than 80 percent of the sediments on the berm surfaces (Fig. 31C). The average beachface slope is 12°, a typical value for gravel beaches.

<u>N-3</u> 25 May 90
Smith Island

A.

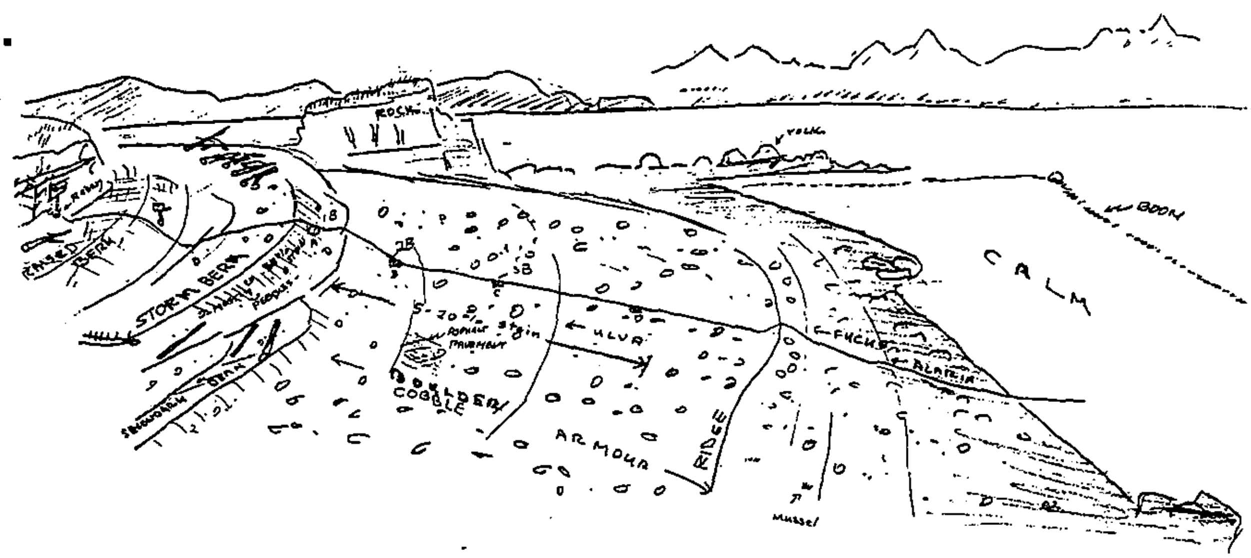
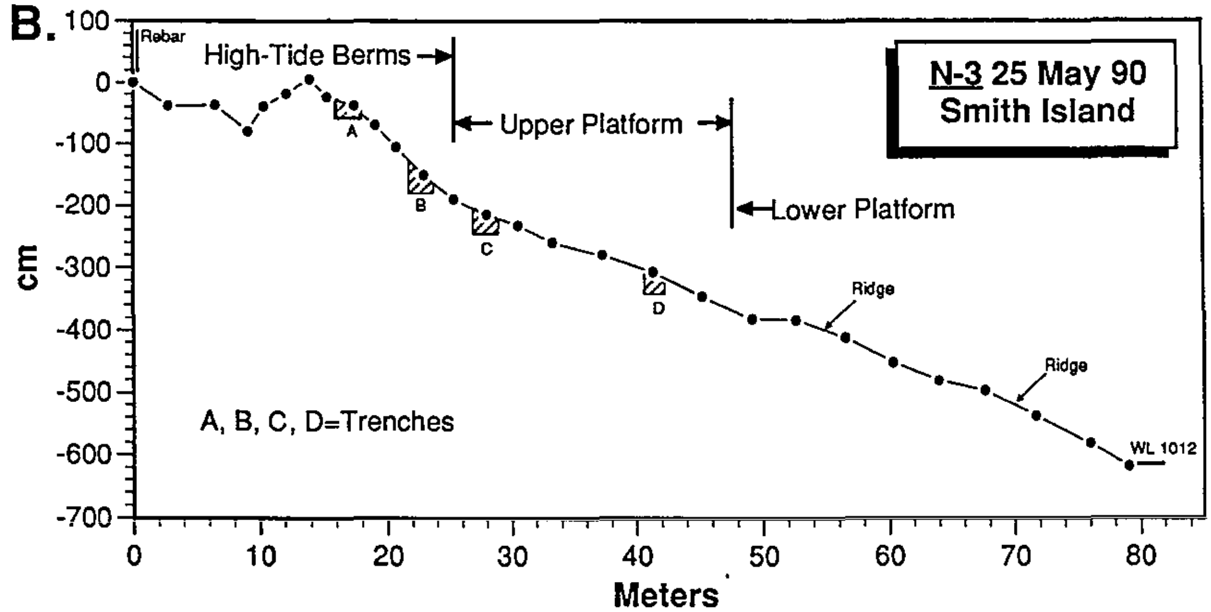


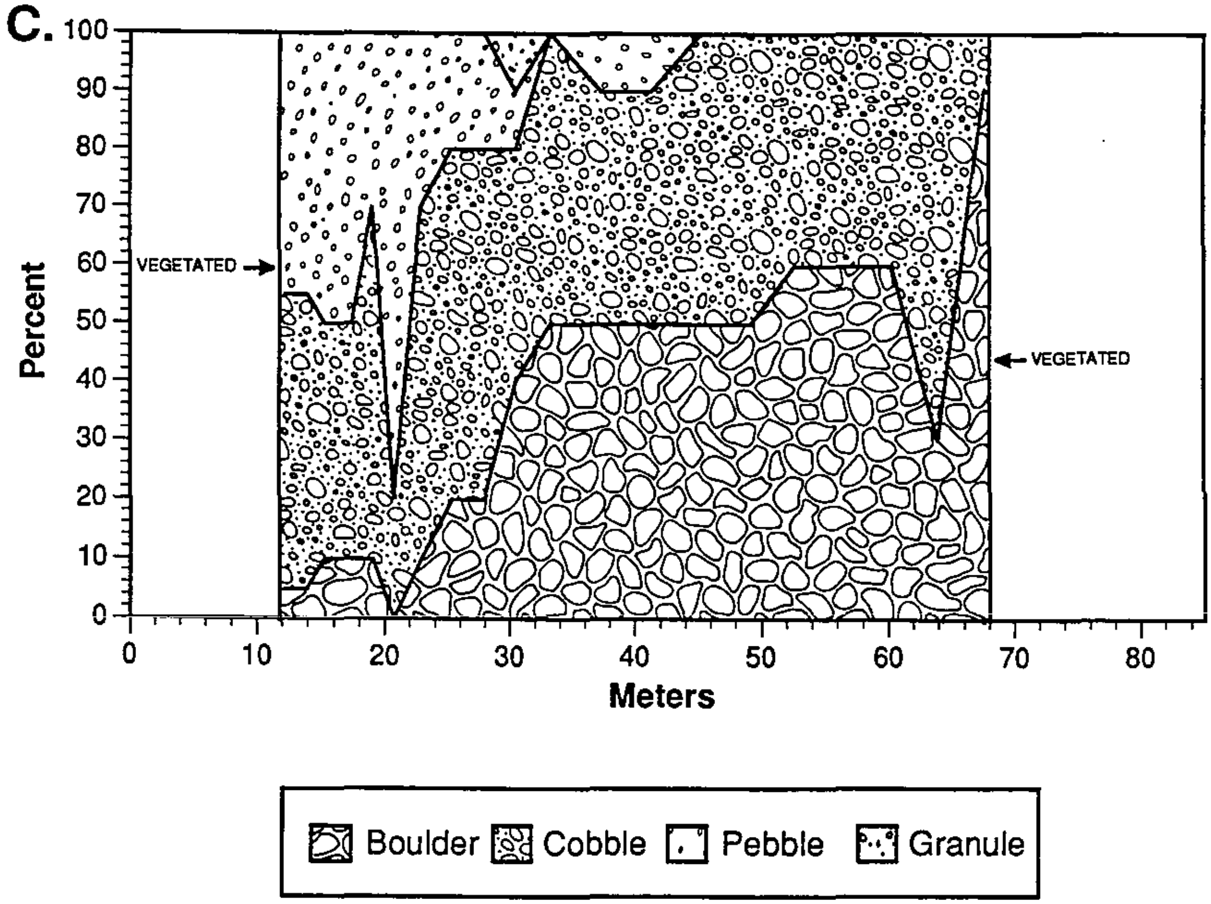
FIGURE 31. Station N-3 at Smith Island on 25 May 1990.

A. Field sketch showing general morphology, sediment distribution, and oiling. Note asphalt pavement on upper platform. The secondary berm near the high-tide line and ridge on the lower part of the profile indicate that sediment motion and deposition has occurred at two levels on the profile.

B. Profile N-3 plotted at 5:1 vertical exaggeration. The profile is divided into three morphological zones—a lower platform which contains two ridges, a smooth-surfaced upper platform, and high-tide berms.

C. Distribution of surface sediments along profile. There is a distinct increase in grain size in an offshore direction, with pebbles being most abundant on the beachface of the secondary (spring-tide) berm and cobbles and boulders dominating the upper and lower platforms.


B.
Rebar
High-Tide Berms
Upper Platform
Lower Platform
N-3 25 May 90
Smith Island
A
B
C
D
Ridge
Ridge
WL 1012
A, B, C, D=Trenches
cm
Meters
100
0
-100
-200
-300
-400
-500
-600
-700
0
10
20
30
40
50
60
70
80


C.
VEGETATED
VEGETATED
Percent
Meters
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
Boulder
Cobble
Pebble
Granule

2) Upper platform

Except for the occurrence of a peculiar mid-tide berm at around the 38 m mark (observed in field notes of 18 October 1989 and 4 March 1990), this part of the profile remained relatively flat throughout the survey period. The surface sediments are mostly cobbles and boulders, and a well-defined surface armor has developed (see trench C in Fig. 34). The slope of the surface of this zone is 4.5° in an offshore direction.

3) Lower platform

This part of the profile, which was frequently covered by the tide during the fall and winter surveys, contained two low-amplitude cobble/boulder ridges on 25 May 1990. Similar berm-like ridges were present in this zone throughout the winter months. The lower platform, which is covered by cobbles and boulders (50/50), slopes seaward at 4°, a slope similar to that of the upper platform. The seaward portion of this zone contains abundant Fucus and Alaria algae. Rock outcrops are present.

FIGURE 32. (Facing Page) Photos of station N-3.

A. West looking aerial view of station N-3 on 25 May 1990. Line indicates approximate location of beach profile survey line. Sediment transport direction is to the west. Photo by M. Hayes.

B. Berm relocation pit on 7 September 1990. Photographer was standing on the profile near high-tide line. View looks east. Photo by J. Michel.

A.

B.

This beach profile was surveyed 8 times (Table 4), and careful inspection of the fall and winter data shows no obvious major discrepancies. As the profile overlay plots given in Figure 35 show, changes on this profile have been rather subtle, compared to station N-1. The crest of the storm berm did not move, though evidence reported during the 18 October 1989 survey indicates that the exceptionally high spring tides of 15-17 October overtopped the storm berm in places, carrying oiled gravel and debris into the backberm area. Sexton, Gibeaut, and Balcom (1990) report that the runnel behind the storm berm was lowered during this event. The interval between the 18 October 1989 and 30 January 1990 showed some small changes, most of which were depositional. Two depositional berms are evident on the 4 December plot (Fig. 35B), a spring-tide berm at just below the snowline and a low berm on the upper platform around the 40 m position. No mention of the second berm is made anywhere in the field notes. The spring berm was still in place during the 30 January 1990 survey, and two berm-like ridges occurred at 45 m and 65 m.

A major erosional event occurred in the interval between the measurement of the 30 January and 4 March 1990 profiles (Fig. 35C). The portion of the profile near the contact between the high-tide berms and upper platform (around 25 m position; Figs. 31B and 35A) was lowered around 40 cm and a concave upward surface was developed. Profile concavity is a clear indication of erosion on most beaches (Hayes and Boothroyd, 1969). The lower part of the profile was lowered also, around 50 cm on the average. With the exception of the formation of a minor spring berm, little change occurred between the 4 March and 25 May 1990 surveys (Fig. 35D). The exposure of an asphalt pavement to the east of the profile in May (see field sketch in Fig. 31A) is further evidence of the erosional event that occurred in February. No significant natural changes occurred on station N-3 during the summer of 1990, as shown by the survey on 7 September 1990. However, the spring berm was relocated in late August as a treatment for the buried oil. The man-induced change of the profile is shown in Figures 32B and 36.

Gravel on this beach was transported readily during the non-summer months of 1989-90, as evidenced by the presence of numerous berms and berm-like ridges on the profile, as well as by the well-sorted and rounded character of the individual clasts. As at station N-1, the potential for a thick vertical section of the gravel on this beach to be mobilized is rather limited, except in the areas of the storm berm and the low-tide ridges. During 1989-90, the maximum thickness of a sediment envelope developed was on the order of 50-70 cm, with three factors contributing: 1) vertical erosion, 2) deposition of berms, and 3) deposition and migration of ridges on the lower parts of the profile.

It is probable that lateral migration of gravel along this profile is considerable, with the primary direction being to the west. The rock outcrop in the center of the sketch in Figure 31A acts as a natural groin to trap gravel moving in that direction (see also aerial view in Fig. 32A). The fact that gravel was eroded from the lower beachface of the storm berm and not transported over the crest is unusual for gravel beaches. Strong longshore transport around the corner to the west is the probable explanation. Another possible explanation would be that the erosion occurred during a neap tide and the berm crest was not overtopped. The berm-like ridges in the lower part of the profile are probably analogous to the swash bars on the lower platform at station N-1, with the shape of the features being modified by wave action on falling tides.

Sediments. The coarse material on station N-3 is derived from erosion of bedrock exposures along the shoreline to the east. No detailed compositional or textural studies were carried out on the sediments of this station. However, the composition does not differ significantly from that at station N-1 (discussed above).

Grain size estimates made at 20 sites along the profile on 25 May 1990 are illustrated in Figure 31C. This plot shows a clearcut increase in grain size in an offshore direction. Pebbles and cobbles dominate the surface sediments of the high-tide berms, boulders and cobbles plus a minor pebble component (<10 percent) prevail on the upper platform, and boulders make up more than 50 percent of the surface sediments on the lower platform, the rest being cobbles. It would appear that the upper platform, which is highly armored, is primarily a sediment bypass zone, rarely hosting depositional features.

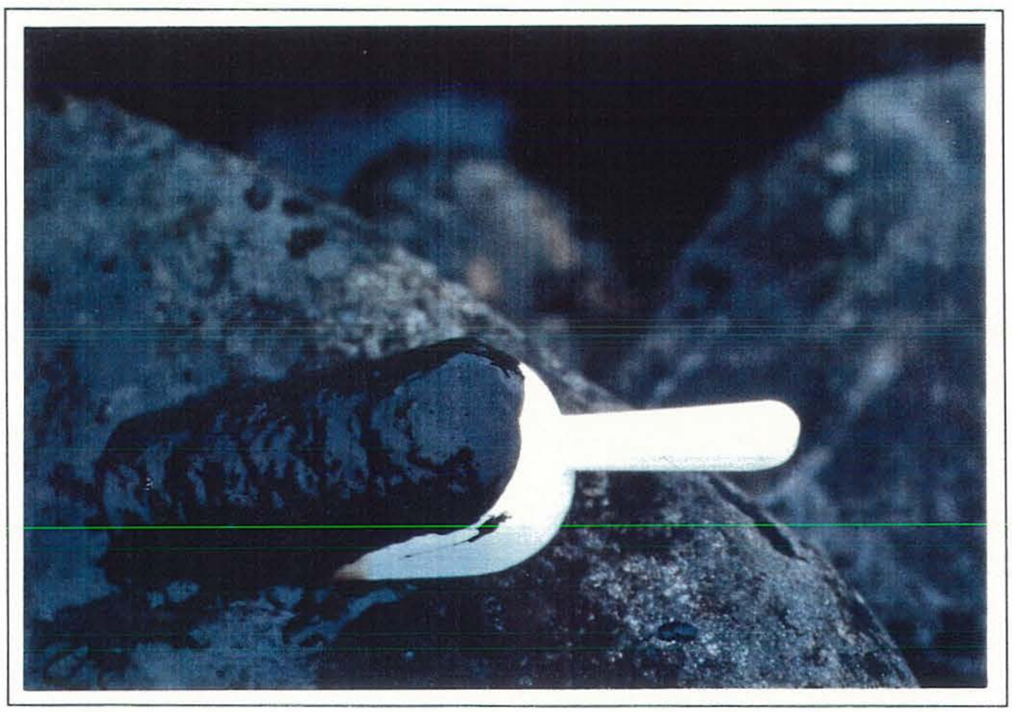
FIGURE 33. (Facing Page) Additional photos of station N-3.

A. Standing oil in bottom of trench at 31 m along profile (upper platform; Fig. 32B) on 18 October 1989. Oil saturated sediments occurred at depths greater than 20 cm. Scale is 15 cm. Photo by D. Hall.

B. Free black oil from bottom of trench on upper platform on 4 December 1989. Photo by D. Hall.

A.

B.



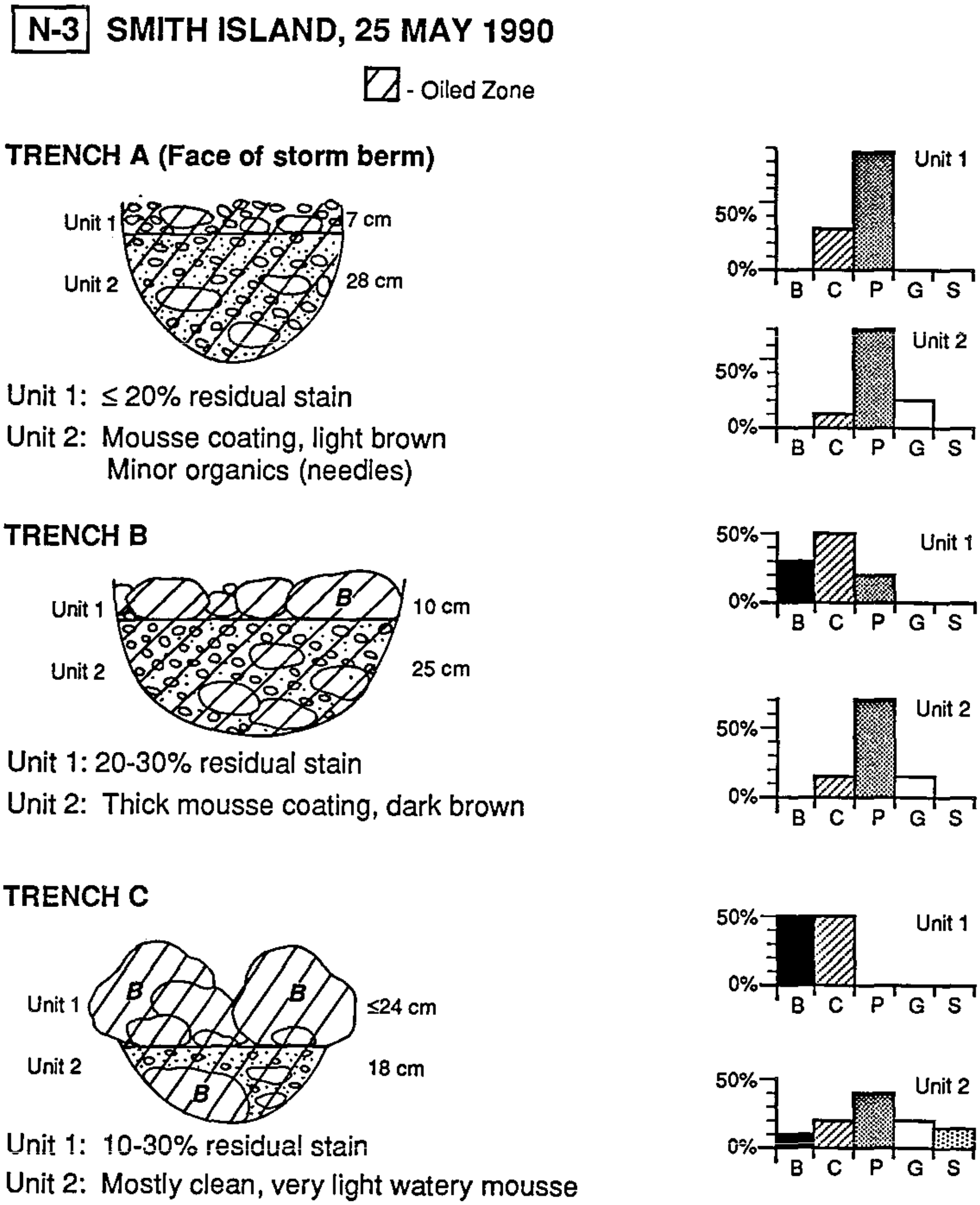


FIGURE 34. Description of trenches dug at station N-3 on 25 May 1990 (see Fig. 31B for location). Both trenches B and C clearly demonstrate the armor that has developed on the surface of the beach at those locations. Most of the oil had been removed at trench C, probably because of vertical erosion in this area of around 50 cm in February.

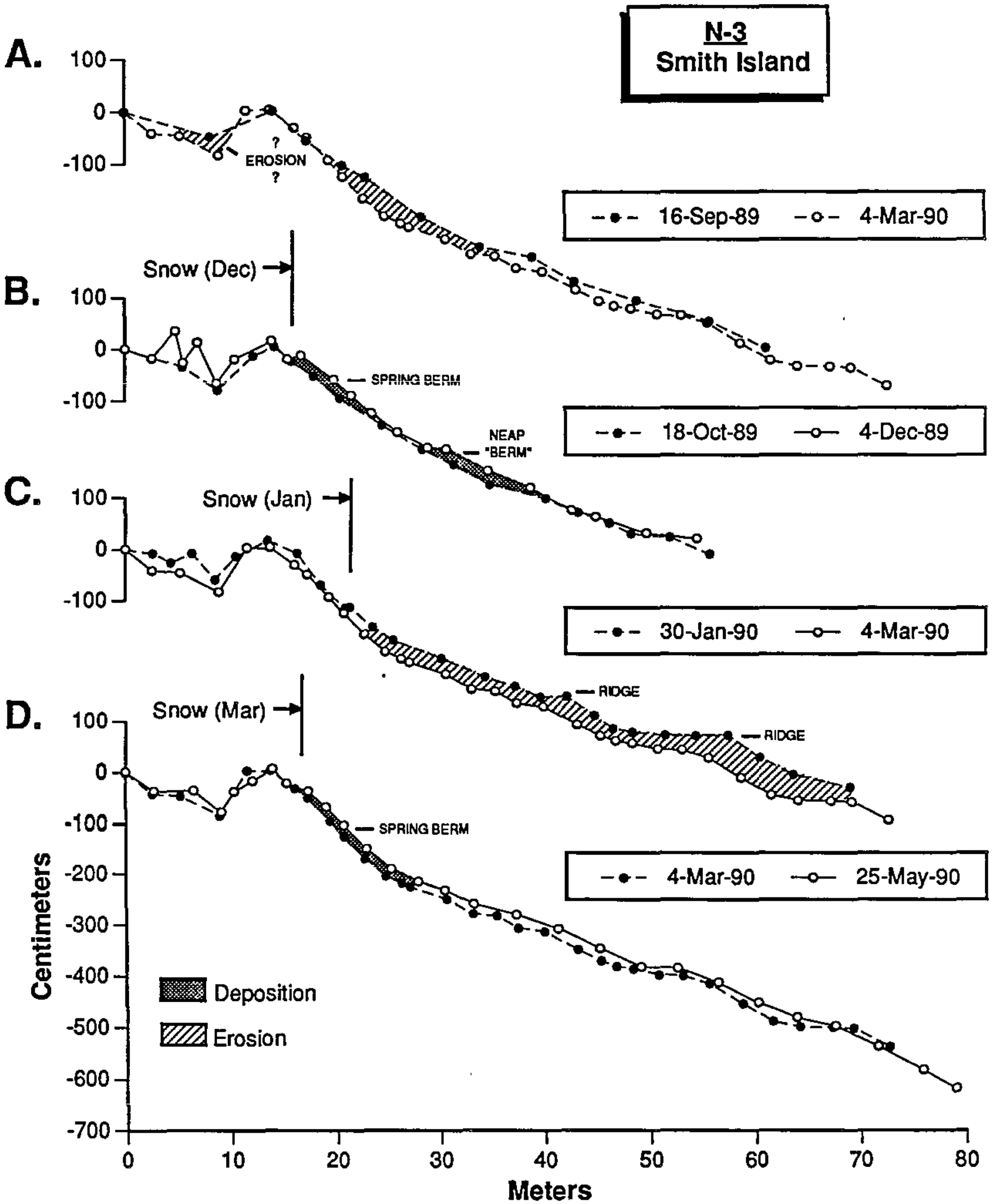
FIGURE 35. (Facing Page) Changes in the beach profile at station N-3.

A. (16 September 1989 and 4 March 1990) Net vertical erosion occurred during the fall and winter months, mostly on the upper platform.

B. (18 October 1989 and 4 December 1989) Note the development of two depositional berms during this interval.

C. (30 January 1990 and 4 March 1990) This interval was the period of maximum vertical erosion. Note also that two large intertidal ridges had developed on the lower portion of the profile between December 1989 and January 1990.

D. (4 March 1990 and 25 May 1990) There was near absence of change in this interval, except for the formation of a minor spring berm before the May survey.


N-3
Smith Island
A.
EROSION
16-Sep-89
4-Mar-90
Snow (Dec)
B.
SPRING BERM
NEAP
"BERM"
18-Oct-89
4-Dec-89
C.
Snow (Jan)
30-Jan-90
4-Mar-90
RIDGE
RIDGE
D.
Snow (Mar)
SPRING BERM
4-Mar-90
25-May-90
Deposition
Erosion
Centimeters
Meters

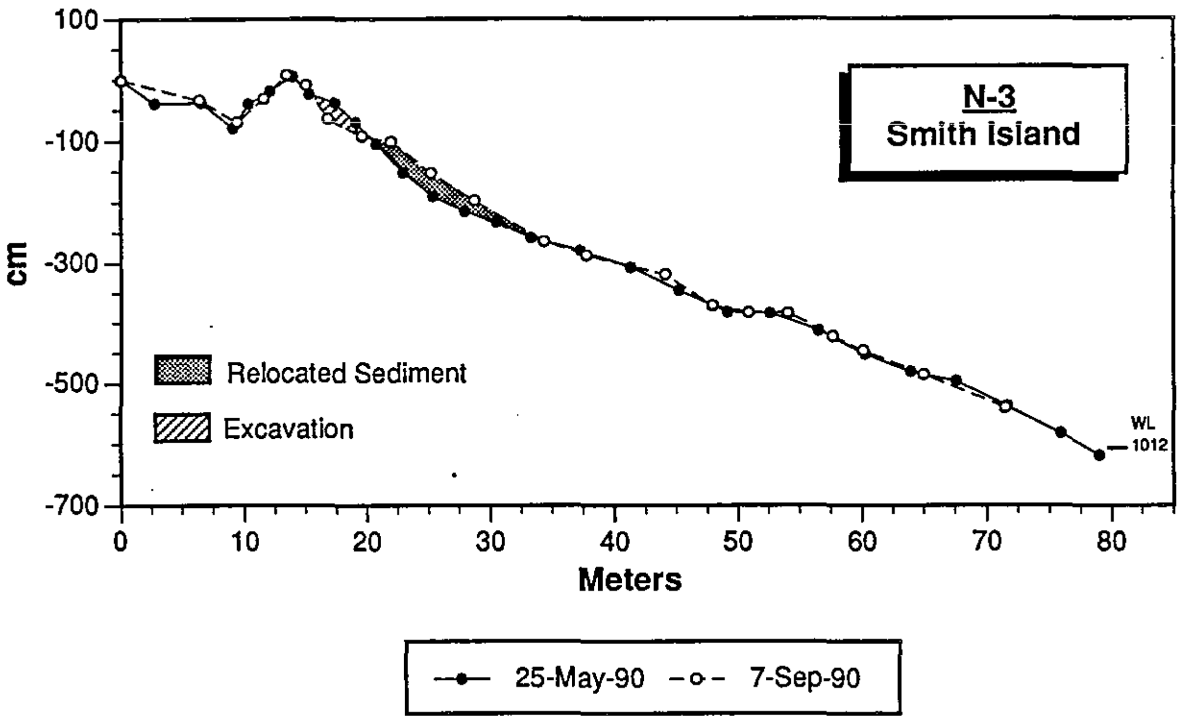


FIGURE 36. Berm relocation at station N-3. The excavation of the top of the storm berm was carried out in late August 1990. The relocated material had not been modified by waves to any significant degree by the time of the 7 September 1990 survey. See photograph in Figure 32B.

A total of 30 trenches were dug on this station during the study. The three dug on 25 May 1990 are illustrated in Figure 34 and the three dug on 7 September 1990 are shown in Figure 37, a remarkable contrast. Excellent armoring was developed on the profile on 25 May, both at the base of the beachface (trench B) and on the upper platform (trench C). The surface material at trench C contained 50 percent boulders and 50 percent cobbles, whereas the underlying layer contained 10 percent boulders, 15 percent cobbles, 40 percent pebbles, 20 percent granule, and 15 percent sand, one of the best developed surface armors observed in the study. Trench A, which was dug high up on the storm berm, did not show armoring because of the rapid vertical accretion that occurs in that area as the high-tide berms migrate up the beach. None of the trenches dug on 7 September (Fig. 37) showed any armoring, because the sediments had been vertically mixed in the process of berm relocation.

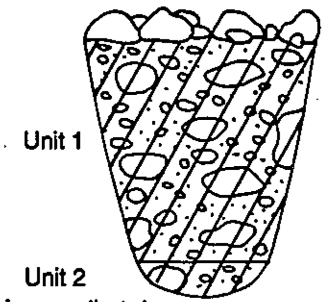
<u>Oil Distribution Patterns</u>. By the end of summer 1989, this site was still heavily oiled. Surface oil coverage was 100 percent from the higher-tide line down to the lower platform (Fig. 38), a width of over 20 m. The rate of removal of surface oil was slow, compared to N-1; there were 10 m of beach with >75 percent oil coverage as late as December 1989. However, by January 1990, surface oil had been reduced to a coating and stain on up to 40 percent of the sediments. This stain was quite persistent; in May 1990, there was 5-20 percent stain on the cobbles (Fig. 38). In September 1990, this zone was covered by the relocated berm sediments. Table 7 lists the sediment TPH results, which show relatively low initial oil concentration on the surface and a general decrease over time. The oil was mostly on the cobbles, so the weight-based concentration of a stain on a cobble is very low. Averaging all the TPH values for surface sediments taken up to December 1989 and comparing them with an average of all the samples taken after that time, there was an 85 percent reduction in the oil content of surface samples.

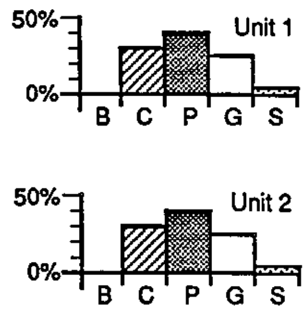
The TPH concentrations of subsurface samples confirm the visual reports of heavy oiling with depth. In both September and October 1989, oil pooled in the bottom of trenches (e.g., Fig. 33A). Samples from throughout the profile in September contained 6,430-43,500 ppm of oil by weight. The highest value represented nearly 7.5 percent oil by volume. The depth of oil at the high-tide berms was never determined, but it was greater than 60 cm, the deepest trench. Free black oil was observed again in December 1989 (Fig. 33B), down to the upper platform where the

N-3 SMITH ISLAND, 7 SEPTEMBER 1990

- Oiled Zone

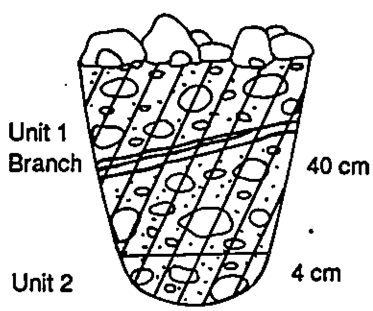
TRENCH A (Berm face)

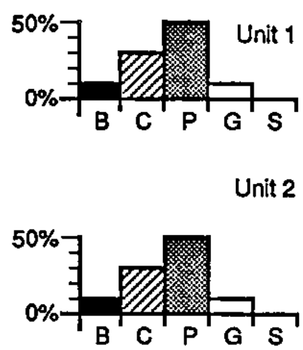




Unit 1: Heavy oil stain
Unit 2: Very light oil stain
Notes: A) Located near center of line of profile
B) Inipol present throughout

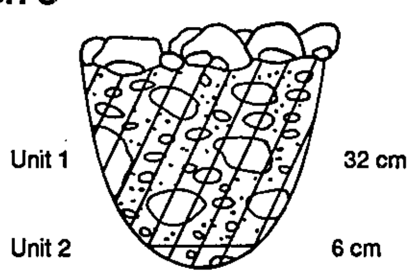
TRENCH B

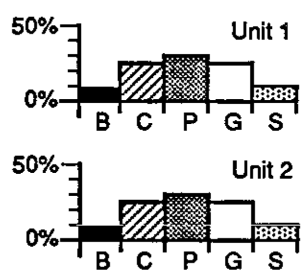




Unit 1: Medium oil stain
Unit 2: Very light oil stain
Notes: A) Inipol present throughout
B) Located near profile line

TRENCH C





Unit 1: Oil droplets and sheen present
Unit 2: Oil pools present
Notes: A) Organics present throughout trench
B) Located near profile line

FIGURE 37. Description of trenches dug at station N-3 on 7 September 1990 (see Fig. 31A for location). Note complete mixing of the sediments as a result of the process of berm relocation.

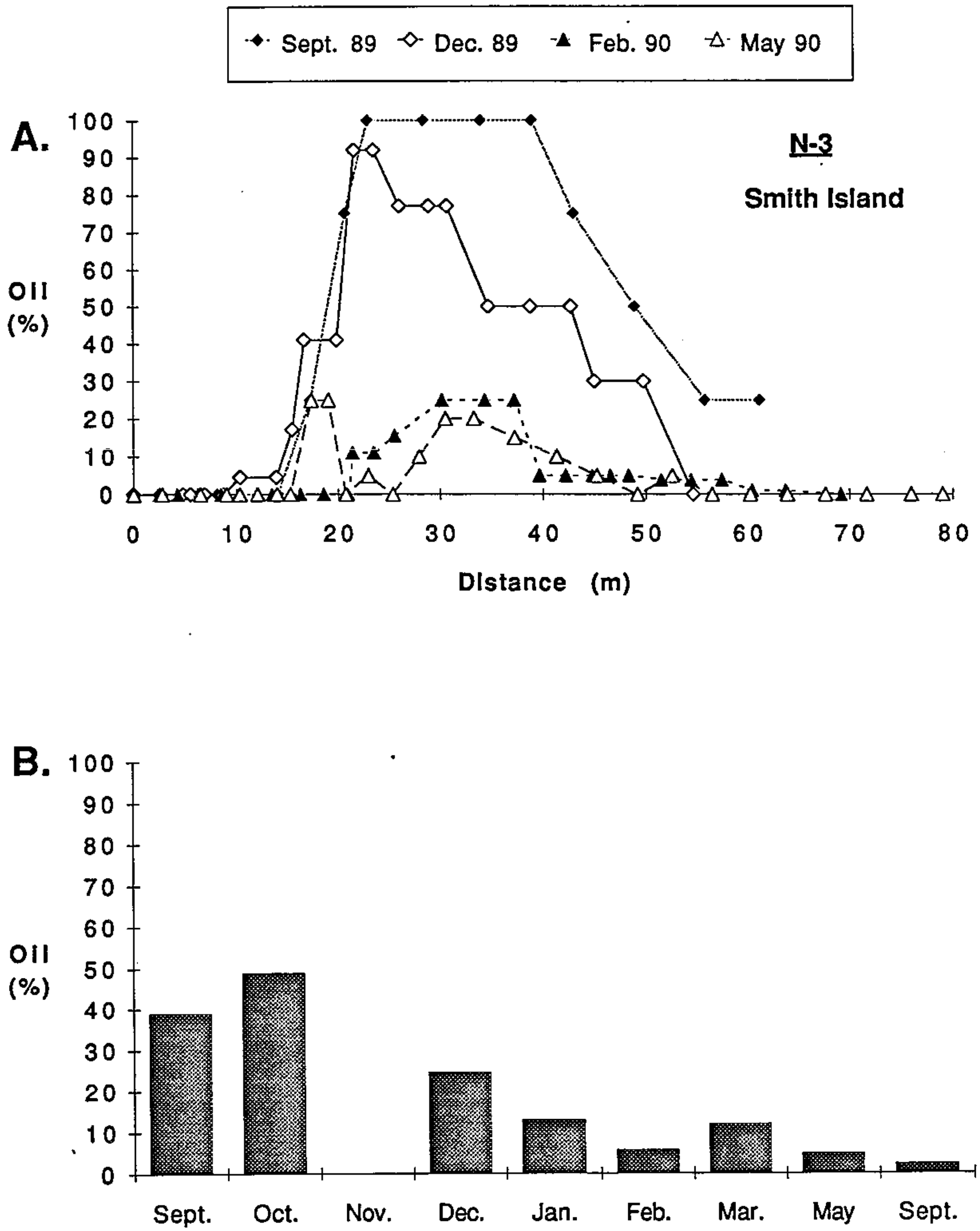


FIGURE 38. Surface oil plots for N-3 on Smith Island.

A. Plots of the percent coverage of surface oil (visual estimate made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

sample from 40-45 cm contained 47,820 ppm TPH by weight, or over 10 percent by volume.

The erosional event between the 30 January 1990 and 4 March 1990 surveys, which removed about 40-50 cm of sediment from much of the profile, removed the subsurface oil in the lower platform and also exposed some of the deeper oiled sediments in the upper platform. Note in Table 7 that TPH values in subsurface sediments from the lower platform went from 13,450 ppm in January to 520 ppm in March. The oil in the lower platform was removed because it was less than 25 cm deep.

By May 1990, there was much less subsurface oil in trenches A-C (Fig. 34). The sediments were uniformly oil-stained or coated with mousse, but no free oil was observed. However, trench D (Fig. 31B) which is still in the upper platform had heavily oiled sediments at 5-15 cm; this zone retained the heavy oil which had penetrated deeply into the sediments and was not removed, only made shallower, by the winter erosion. Therefore, this zone still has a relatively shallow layer of heavily oiled sediments at a somewhat unusually low position on the beach. Note that sorbent booms had to be placed around this section of shoreline because it was a frequent "sheener" (Fig. 32A). Oil still remained in the high-tide and storm-berm zones, thus the decision for berm relocation in late August 1990. However, examination of Figure 36 shows that the relocated berm sediments have been piled and left on top of the upper half of the upper platform, a zone itself which has high concentrations of subsurface oil. The relocated sediments will surely slow removal of this subsurface oil. The likelihood of extensive reworking of sediment below the armor is slight; in 1989/90 only one storm event caused significant erosion in the central zone.

Observations on Biota. Biological studies by NOAA were begun on this site in 1990. The mid-tide quadrats are located at about the 37.5 m position on the profile (Fig. 31), and the low-tide quadrats are located at about 51 m (Fig. 31B). Both positions are in or just below the zone of the highest subsurface oil on the profile. The low quadrats are in the swale in front of the first ridge. It is likely that this low area is more protected from wave attack than other parts of the beach. But, it is also possible that oil contaminated water draining from the oiled sediments could concentrate or even pool in this shallow swale.

TABLE 7. Sediment TPH (in ppm) results for N-3 on Smith Island by morphological zone.

Surface Samples

Date	High-Tide Berms	Upper Platform	Lower Platform	Mean
9/89	580	700/150	320	440
10/89	160			
12/89	900/210			560
1/90		70/110	80	90
2/90	60	50		60
3/90	120	50/50	10	140

Subsurface Samples

	High-Tide Berms		Upper Platform		Lower
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	Platform
9/89		8,860/11,430	14,620	43,500	23,960/6430
10/89		4,050		5,200	
12/89		6,900/3,280	410	47,820	14,430
1/90		22,690	3,960	14,530	13,480
2/90	2,650	5,080	16,300		520
3/90	210	3,540	7,700	8,260/5,630	20
9/90		7,640		10,170	

Station N-4

Introduction. Located one-third of the way from the east end of Smith Island, this station shares some similarities with station N-3. It has almost the same exposure to wave action, ± 10 km effective fetch in a due northerly direction, and a 40-45 km fetch line in a northeasterly direction which strikes the coast at a 50° angle. Because it is closer to the east end of the island, this station could be subject to greater wave action than N-3 from storms with predominantly easterly winds.

Station N-4 is primarily an uplifted shore platform with minor berms at the high-tide line. The area was uplifted 1.5 m during the 1964 earthquake. An uplifted wave-cut scarp occurs immediately behind the beach (Fig. 39), a clear testament to the erosional history of the area. Sediment appears to be in short supply in comparison to N-3, as seen by the sparse sediment in the berms and abundance of exposed bedrock along the uplifted shore platform. A field sketch, beach profile, and sediment distribution plot for the profile on 25 May 1990 are given in Figure 39 and selected photographs are given in Figures 40 and 41.

Like N-3, the shoreline was heavily oiled on 27 March 1989, and it was a chronic "sheener". Cold-to-hot water washing was conducted on this segment several times during 1989. This site was a hot-water control during the Corexit 9580 operational tests in August 1989. Inipol and Customblen were used in both 1989 and 1990; the 1990 application was used in conjunction with berm relocation in August.

Morphology and Beach Dynamics. There are three major, morphologically distinct components of this profile:

1) High-tide berms

The interval between 4 and 15 m on the profile (Fig. 39B) contained from one to three berms each time the profile was measured. There is no major, primary storm berm like the ones at stations N-1 and N-3. The berms were usually composed of highly mobile pebbles and small cobbles (Fig. 40). The average slope of the beachface was 17.5 °.

N-4 25 May 90
Smith Island

A.

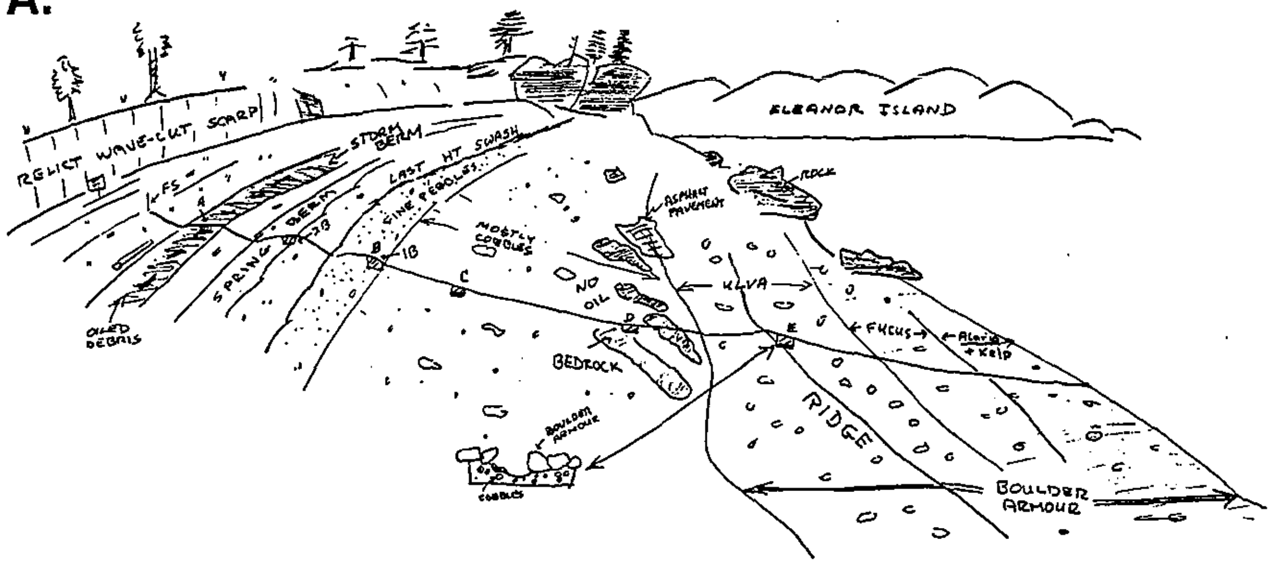


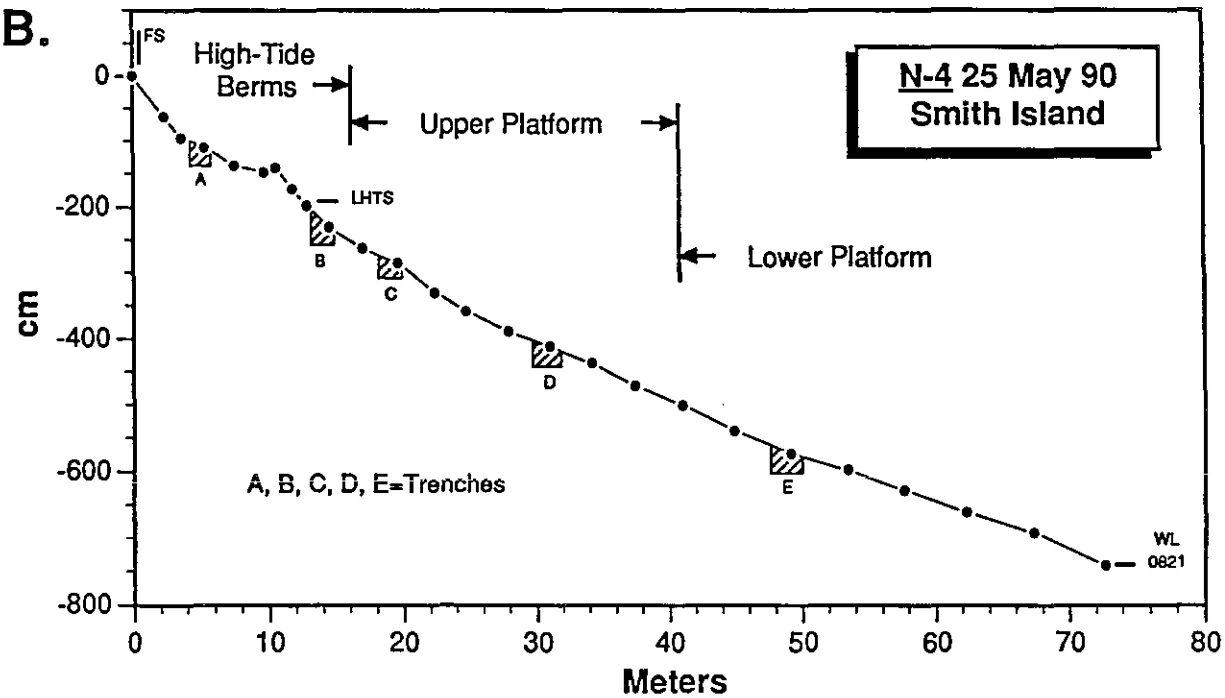
FIGURE 39. Station N-4 on 25 May 1990. Oil was restricted to the high-tide berm zone at this time.

A. Field sketch. Note bedrock outcrops in center of profile, asphalt pavement in middle distance, and heavy algal growth near low water. A boulder armor is well-developed on lower platform.

B. Topographic profile of the relatively featureless beach. Berms are small relative to stations N-1, N-3, and N-7.

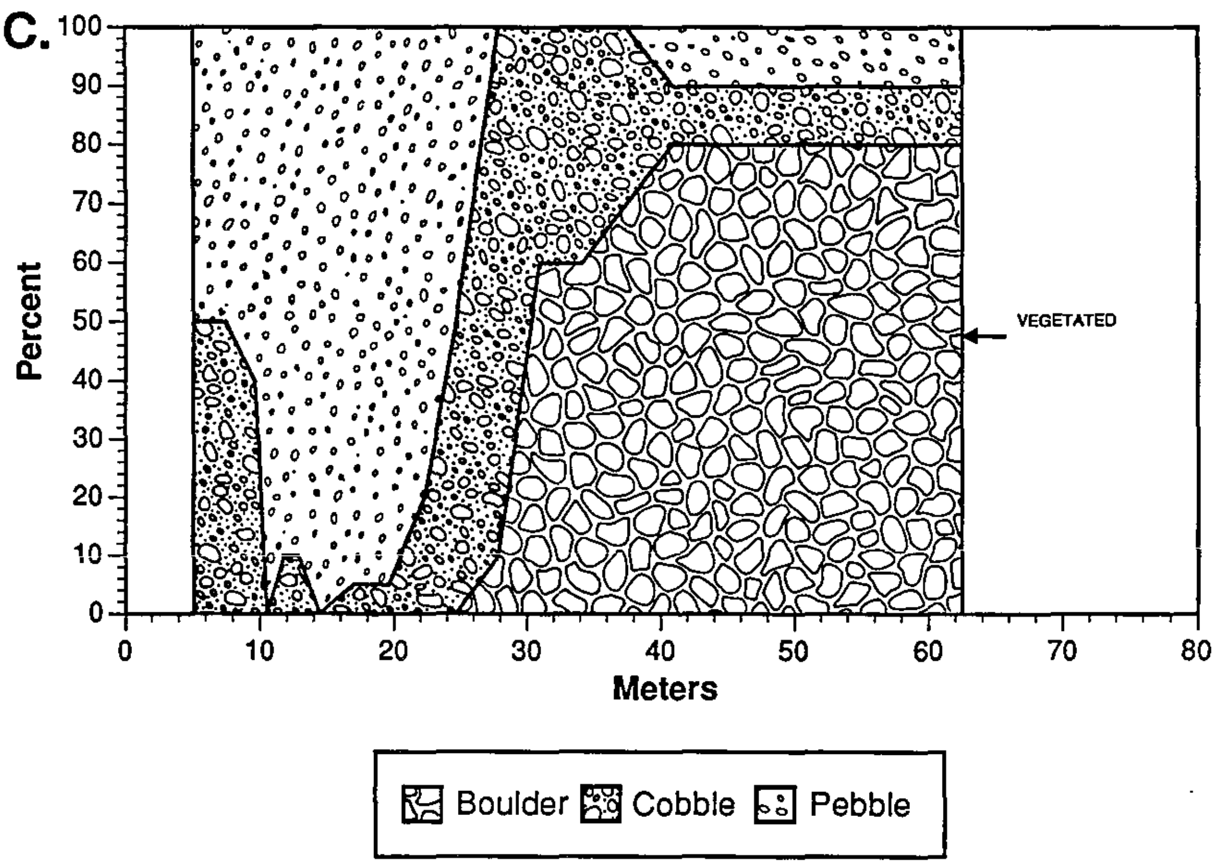
C. Surface sediment distribution along profile, showing a strong gradient of fine-to-coarse material in an offshore direction.

B.



N-4 25 May 90
Smith Island
High-Tide Berms
Upper Platform
Lower Platform
LHTS
FS
A, B, C, D, E=Trenches
WL 0821
cm
Meters

C.



VEGETATED
Percent
Meters
Boulder
Cobble
Pebble

2) Upper platform

A thin veneer of gravel overlies a bedrock surface that crops out at several localities in this zone (Fig. 39A), which extends from 15 to 47 m along the profile and dips seaward at 6°. Obviously, the potential for wave erosion on a seasonal basis of such a zone is nil. There is a striking gradient in grain size across this part of the shore platform (Fig. 39C), with pebbles and cobbles dominating the upper half and boulders the lower half. Surface armor is well-developed only on the lower part of this zone (Fig. 41A).

3) Lower platform

This surface, which also contains a number of bedrock outcrops, dips seaward at a somewhat lower angle (4°) than the upper platform. Boulders make up 80 percent of the highly armored surface sediments and the lower part has a dense growth of Fucus, Alaria, and kelp. Subtle berm-like ridges occurred from time to time (Fig. 39A), but no major sediment thicknesses developed over the bedrock surface, and the ridges were barely perceptible on the plotted profiles.

The beach profile at station N-4 was surveyed eight times (Table 4). For the most part, the fall and winter surveys appear to be accurate, with the exception of an obviously erroneous vertical reading in the October survey. Because of the presence of snow, a new front stake was added about 5 m seaward of the previously used starting stake during the 1 January 1990 survey. Unfortunately, this new stake was never tied to the original back stake (not recorded in notes, in any event), thus it is not possible to precisely overlay the pre- and post-30 January profiles.

FIGURE 40. (Facing Page) Photos of station N-4.

A. Oblique aerial view looking west on 25 May 1990. Note raised armored cobble/boulder platform. Line gives approximate location of beach profile measured at this station. Photo by M. Hayes.

B. Ground view looking west from high-tide berm area of profile on 25 May 1990. This is the zone of active sediment motion on this beach. Photo by J. Michel.

A.

B.

The series of beach overlays shown in Figure 42 clearly demonstrate the relatively minor changes that occurred along this profile. The upper beach at this station was washed heavily in late August 1989, and an apron of finer gravel (pebbles and cobbles) covered much of the upper platform at the time of the 17 September 1989 survey. The 18 October 1989 survey (Fig. 42A) showed that some of that material had been remobilized into a high, cobble "storm" berm at the 5 m mark during the high spring tides of mid-October. The depositional process apparently continued into December, and a moderately large, cuspate pebble berm was present at the 10 m mark (normal spring-tide level) during the 4 December 1989 survey. An erosional episode occurred before the 30 January 1990 survey, when the aforementioned spring berm was missing. Instead, a well-defined neap berm was present at the 16 m mark and a veneer of pebbles covered most of the upper platform. By 30 January 1990, the sediment of the neap berm was apparently moved landward approximately 10 m to form a new high-level berm. We assume that the early February 1990 storm that eroded station N-3 also impacted this beach, but by the date of the next survey, 4 March 1990, a constructional profile consisting of a new "storm" berm and a spring berm was present. The profile continued to accrete up to the date of the 25 May 1990 survey (Figs. 39 and 42D). The upper beach was changed significantly by a berm relocation treatment in August 1990, as can be seen on the plot of the 1 September 1990 profile (Fig. 43). By 1 September, the seaward portion of the relocated sediment had been molded into a smooth, concave-upward surface and a minor berm had been formed on the landward side. Therefore, the potential for sediment mobilization on this profile is considerable, particularly for cobbles and pebbles. Even so, the sediment envelope observed to develop on this profile is small, achieving a maximum thickness of around 30 cm near the high-tide line by virtue of berm formation and erosion. The veneer of sediment on the bedrock of the upper and lower platforms remained relatively thin, even though subtle berm-like ridges did occasionally form (see sketch in Fig. 39A), and no significant sediment envelope was measured.

One would assume the dominant direction of longshore transport at this station to be westerly, because of the predominant easterly winds, but no data were collected that clearly indicates such a trend. Instead, there appears to be a potential for waves to refract around a headland on the east side of the beach and form a sediment transport reversal to the east near the center of the beach. The eastern side of the beach is definitely more sheltered, as evidenced by the persistence of an asphalt pavement in the eastern corner. Thicker depositional berms to the east also indicate transport in that direction.

Sediments. The gravel on this beach is no doubt derived locally from erosion of adjacent headlands. No detailed study was made of clast composition, but a range of metamorphic rock types crop out in the local area. Surface sediment grain size distribution was estimated at 20 sites along the profile on 25 May 1990. As can be seen in Figure 39C, one of the most pronounced grain size changes seen in the study area occurs along this profile. Except for the cobbles that make up 50 percent of the storm berm, the high-tide berm zone is covered almost completely by pebbles. The surface of the middle of the upper platform is covered mostly by cobbles and the lower platform surface is 80 percent boulders.

Twenty-four trenches were dug at this station over the fall and winter monitoring period, and their descriptions contribute to the discussion of oil distribution (below). A trench located near the middle of the upper platform on 25 May 1990 (trench D; Figs. 40A and 40B), showed the following armored structure:

	boulders	cobbles	pebbles	granules	sand
surface layer (percent)	30	60	10		
underlying layer (percent)		5	40	45	10

The entire lower platform showed armoring of this nature in May. No armoring was present in any of the trenches dug during the 1 September 1990 survey, as all of them were in the area disrupted in the process of berm relocation.

FIGURE 41. (Facing Page) Additional photos of station N-4.

A. West-looking view over middle of highly armored platform on 25 May 1990. Note good rounding and moderate sorting of the boulders and cobbles. Photo by J. Michel.

B. Trench C near the low water level on the lower platform on 1 January 1990. This previously oiled area had been cleaned by this date so no subsurface oil was observed. Photo by E. Nigg.

A.

B.

Oil Distribution Patterns. The mobility of the high-tide berms affected the distribution of surface and subsurface oil at N-4. Figure 44 shows the distribution plots of surface oil coverage. After the final hot-water washing in September 1989, 50 percent of the pebbles and 50-75 percent of the boulders were covered by a thin oily film. The high tides in October 1989 pushed a band of oil and oily debris onto the low "storm" berm, where it remained (sometimes buried by snow) through May 1990. The surface sediments were never heavily oiled from September 1989 on, as shown in Table 8; most samples had less than 10 ppm TPH. In May 1990, the only visible surface oil was on the storm berm. Throughout the survey, the surface oil was always described as a light film, much different from the black coating of oil or mousse on the cobbles at N-3.

The distribution of subsurface oil was also quite different from N-3. During the September 1989 survey, clean sediments were reached in the bottom of all trenches: oil extended to 50 cm at the high-tide berms, and to 20-25 cm on the platforms. The depth of oil was controlled primarily by the depth to bedrock. The highest TPH levels measured in September 1989 was 4,230 ppm at 10-12 cm depth in the upper platform. Sediments in the lower platform were obviously contaminated by the transport of oiled sediments into this zone during treatment, as evidenced by 170 and 480 ppm oil. However, TPH concentrations dropped to very low levels by January 1990. The reworking of the berms gradually affected the subsurface oil deposits, although sheens and spots of oil continued to be observed in the substrate all winter. Oil concentrations greater than 1,000 ppm were found at depths >25 cm at the high-tide berms in February. In March 1990, the oiling in the high-tide berm trench was described as uniform with depth, as a light sheen and occasional oil spot. The sample from 45-50 cm contained 270 ppm TPH, and the sample from 15-20 cm contained 90 ppm. Thus, the early February storm must have eroded the sediments and removed most of the subsurface oil on this beach. The persistence of a large asphalt pavement in the eastern pocket further supports the conclusion that waves generated during easterly storms eroded the beach. A sample from the storm berm, at 65-70 cm, contained 1,110 ppm TPH, indicating the possible presence of truly buried oil, rather than oil which had penetrated from the surface.

Little had changed by May 1990; the trench descriptions show the heaviest oil in the storm berm and trace oil in the active berm, but otherwise the sediments were clean. In September 1990, relocation of the berm redistributed the subsurface oil to the surface and oil-stained pebbles extended across the upper platform. Figure

43 shows that the relocation work actually only and properly relocated the entire storm berm to the high-tide berm zone. The storm berm excavation was limited to those sediments above normal high tides. The sediments were not spread down to the upper platform, thus limiting the potential for further burial of subsurface oil.

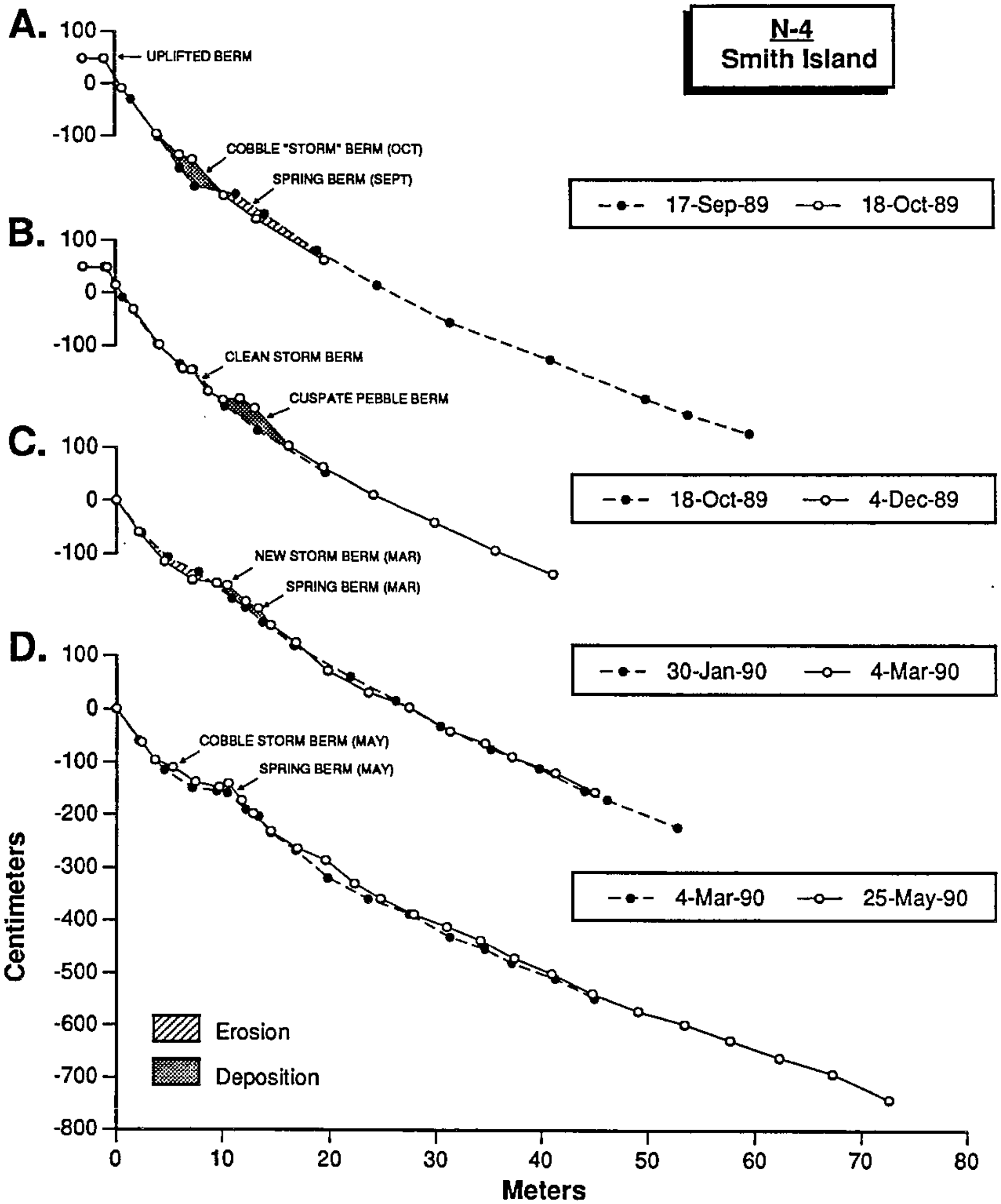
FIGURE 42. (Facing Page) Comparison of beach profiles surveyed at station N-4.

A. (17 September 1989 and 18 October 1989) The moderate-sized spring berm present in the September survey was apparently remobilized during the high spring tides of mid-October and a new high-level cobble berm was formed, which is referred to as a "storm" berm in the field notes.

B. (18 October 1989 and 4 December 1989) A well-developed cuspate pebble berm had formed by 4 December near the same position as the spring berm on 17 September (see plot A).

C. (30 January 1990 and 4 March 1990) A new front stake was established on 1 January. Apparently, a major erosional event occurred between these surveys, but a double berm system had formed by 4 March.

D. (4 March 1990 and 25 May 1990) Accretion continued during this interval, and both berms were elevated somewhat.



N-4
Smith Island
A.
UPLIFTED BERM
COBBLE "STORM" BERM (OCT)
SPRING BERM (SEPT)
17-Sep-89
18-Oct-89
B.
CLEAN STORM BERM
CUSPATE PEBBLE BERM
18-Oct-89
4-Dec-89
C.
NEW STORM BERM (MAR)
SPRING BERM (MAR)
30-Jan-90
4-Mar-90
D.
COBBLE STORM BERM (MAY)
SPRING BERM (MAY)
4-Mar-90
25-May-90
Erosion
Deposition
Centimeters
Meters

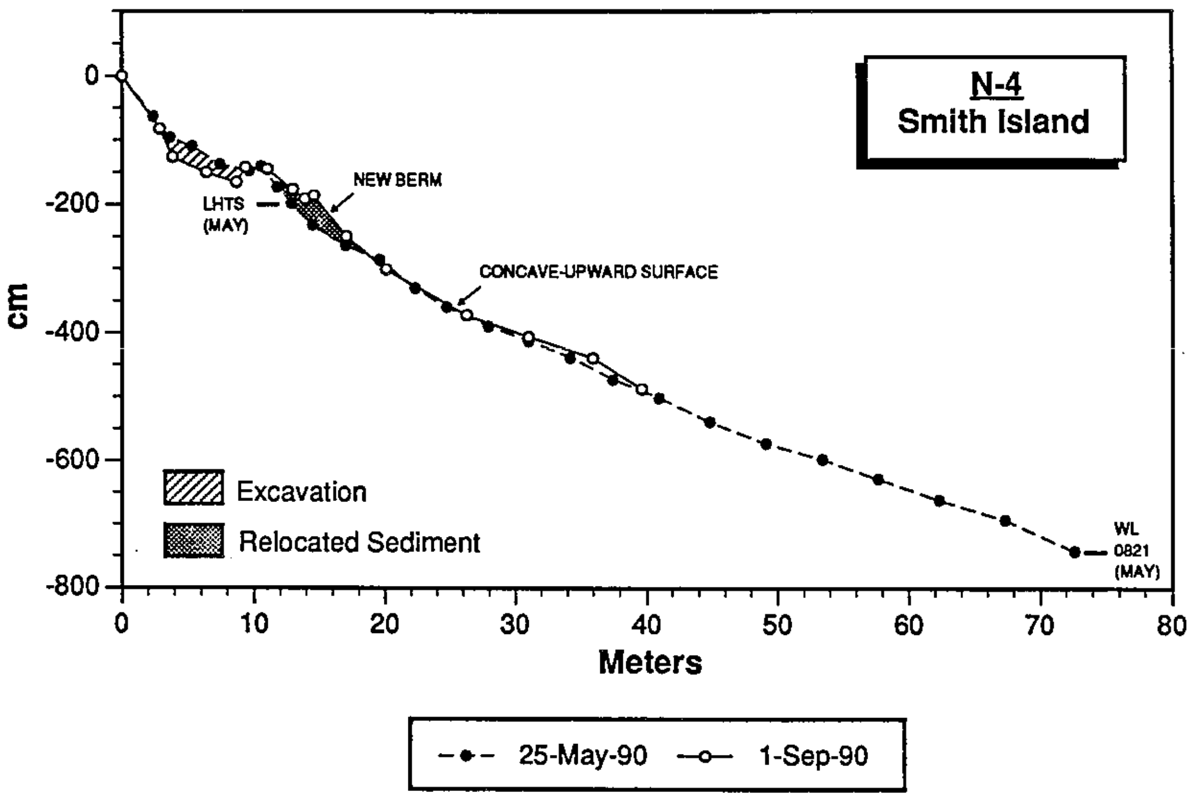


FIGURE 43. Berm relocation at station N-4. The relocation was done in late August. By the time of the 1 September 1990 survey, some of the excavated material had been shaped into a new berm by the waves.

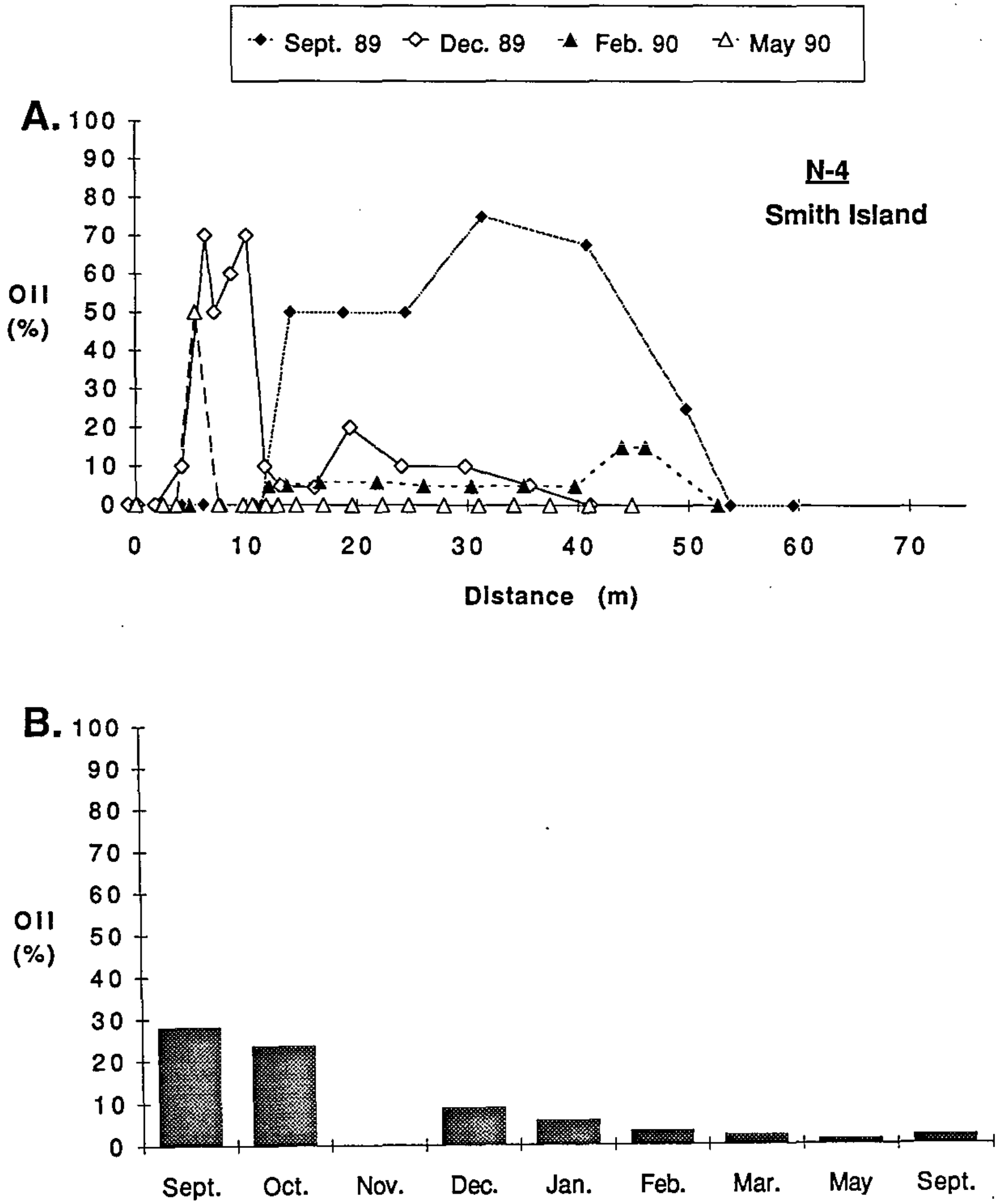


FIGURE 44. Surface oil plots for station N-4 on Smith Island.

A. Plots of the percent coverage of surface oil/visual estimates made in the field for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 8. Sediment TPH (in ppm) for N-4 on Smith Island by morphological zone.

Surface Samples

Date	High-Tide Berms	Upper Platform	Lower Platform	Mean
9/89		490		
10/89	120	40		80
12/89	20/470	50		180
1/90	630	30	20	230
2/90	60	50	70	60

Subsurface Samples

	High-Tide Berms		Upper Platform		Lower
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	Platform
9/89	990/3,250		680/1,160/4,230		170/480
10/89		480	405	360	
12/89	270/1,720	380/830	60	40	
1/90		0/340		3,810	50
2/90		1,140/1,350		50/70	10
3/90	90	270	60		60

Station N-7

<u>Introduction</u>. Station N-7 is located on the east-west oriented pocket beach on the north side of the major headland to the north of the entrance to the Bay of Isles, Knight Island (Fig. 16). This station is more sheltered than it would appear from the general map. There is no westerly exposure to wave action and the maximum effective fetch to the north is only 5 km. Smith Island, to the northeast, Seal Island to the east, and complex local offshore shoals combine to limit the exposure to waves from the east. There is an open effective fetch to the northeast (40° to the beach) of 15-20 km, and to the east-northeast (70° to the beach) of around 60 km. It is clear from the more angular and less well-sorted character of the gravel on this

beach that significant wave action is limited to major storms. The overall morphology, however, is similar to the other stations in this class (i.e., N-1, N-3, N-4, N-15, and N-17). Like the other stations, this site contains an uplifted shore platform infrastructure, as a result of the 1.2 m of uplift during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the profile on 25 May 1990 are given in Figure 45 and selected photographs are presented in Figures 46 and 47.

This area was very heavily oiled in late March 1989, when the major slicks were transported along the eastern shore of Knight Island. Shoreline treatment in 1989 consisted of hot-water washing and nutrient addition. In 1990, this pocket beach was selected as the Customblen-only monitoring site, part of the Exxon/USEPA/ADEC bioremediation effectiveness monitoring program (Prince, Clark, and Lindstrom, 1990). The site was selected because it had little surface oil, but still contained heavy subsurface oil. Monitoring wells were installed to sample intertidal water for nutrients and bacteria biomass. On 30 May 1990, half the pocket beach was treated with Customblen; the other half received no treatment. NOAA's profile is located on the boundary line between the two sections. Customblen application was made on 13 July 1990. Finally, the entire segment was treated, on an experimental basis, with Inipol on 8 September 1990 (2 days after our September 1990 visit).

N-7 25 May 90
Knight Island

A.

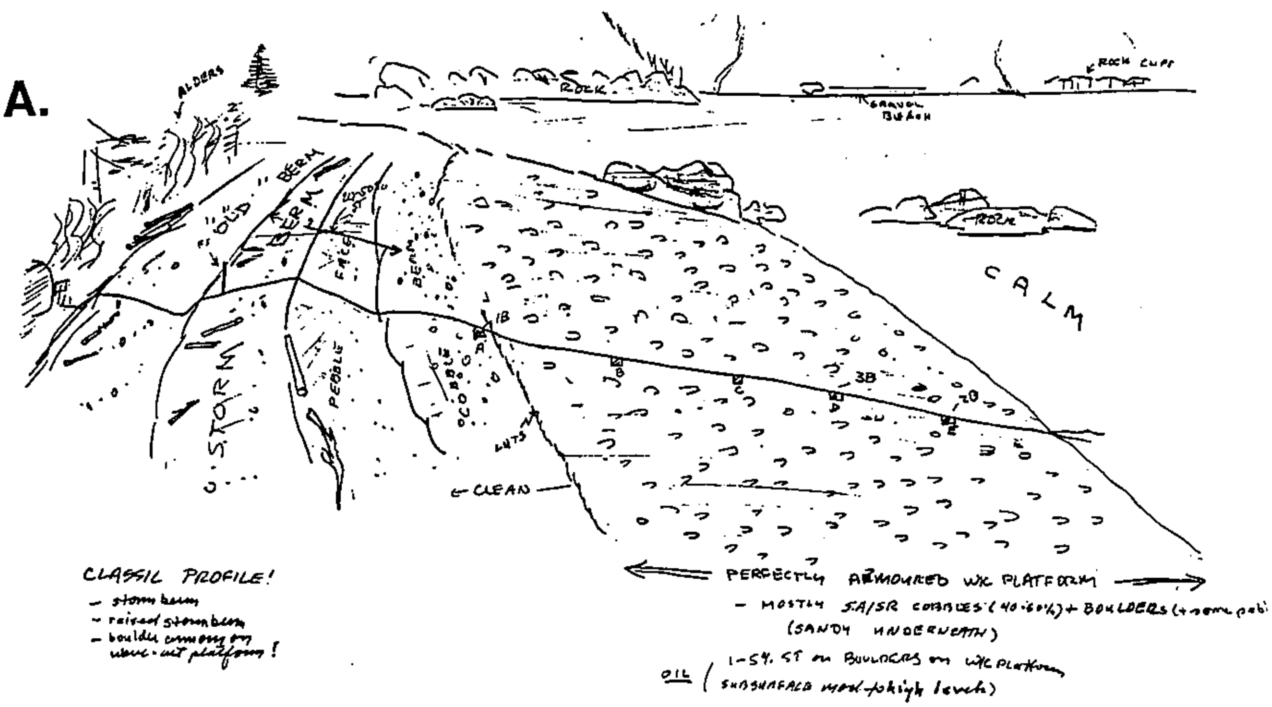
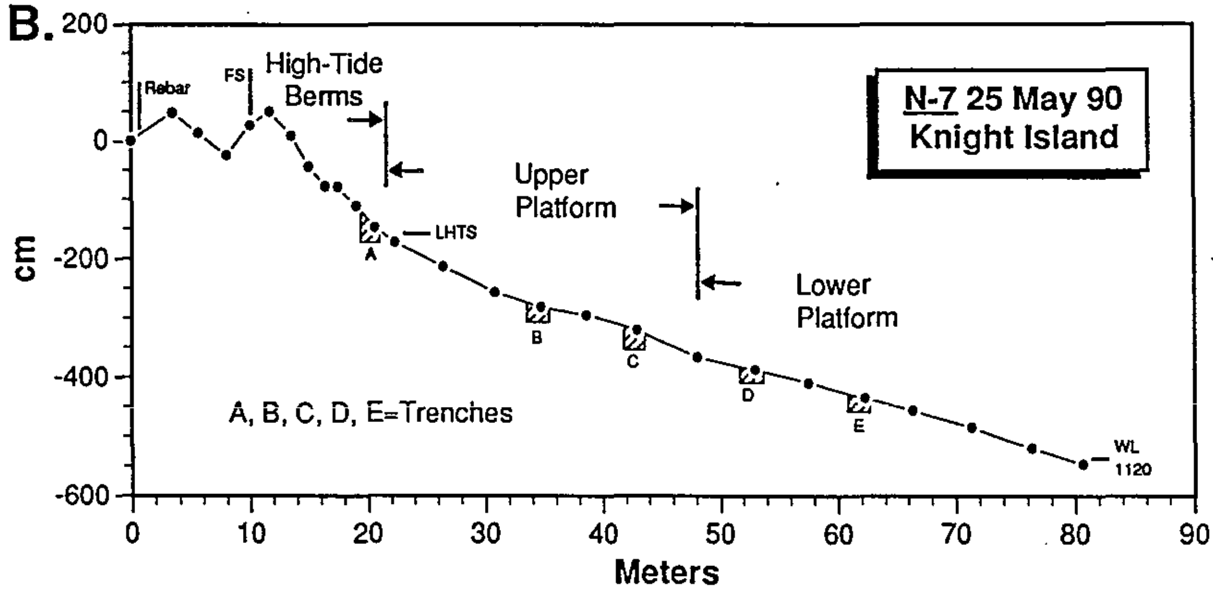


FIGURE 45. Station N-7 on 25 May 1990.

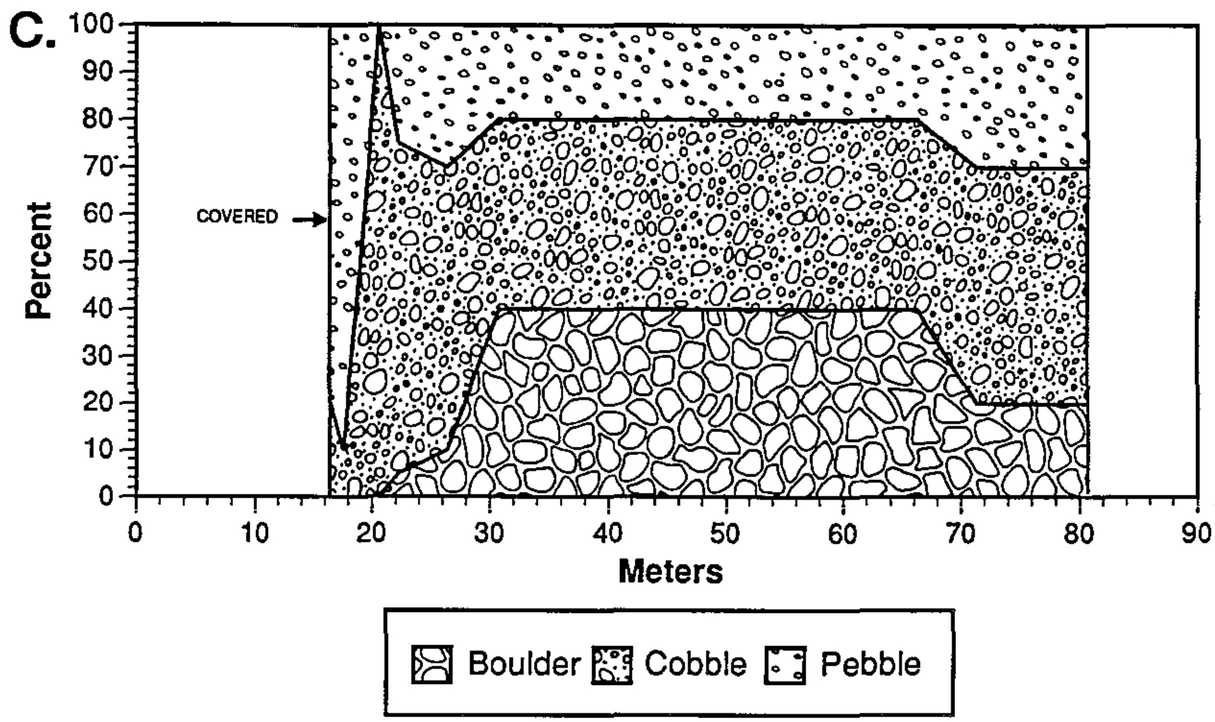
A. Field sketch showing a classic armored raised shore platform backed by a series of high-tide berms. The most landward, highly vegetated berm is at about the same height as the active storm berm. Biota are relatively sparse on this profile.

B. Topographic profile which shows the well-developed active storm berm, as well as the different slopes of the upper and lower platforms.

C. Distribution of surface sediments across the profile, showing the dominance of pebbles and cobbles on the surface of the high-tide berms and important boulder component of surface sediments of the upper and lower platforms.



B.
N-7 25 May 90
Knight Island
Rebar
FS
High-Tide Berms
LHTS
Upper Platform
Lower Platform
A, B, C, D, E=Trenches
WL 1120
cm
Meters



C.
COVERED
Percent
Meters
Boulder
Cobble
Pebble

Morphology and Beach Dynamics. There are three morphological components of this station:

1) High-tide berms

   The station had two berms at the storm-berm level, with the more landward one being highly vegetated (i.e., inactive). The seaward storm berm, which is 1.2 m high, did not change significantly over the monitoring period, but it is obviously subject to change during major storms. A spring berm was present near the level shown on the sketch and profile of Figure 45A and B from the 18 October 1989 survey forward. The average slope of the beachface of the storm and spring berms, which usually had surface sediment layers of pebbles and cobbles, was 15°.

2) Upper platform

   This zone, which lies between 22 and 50 m on the profile (Fig. 45B), is an undulating surface armored with boulders and cobbles over a sandy substrate on the bedrock platform. It slopes offshore at an angle of 5°.

3) Lower platform

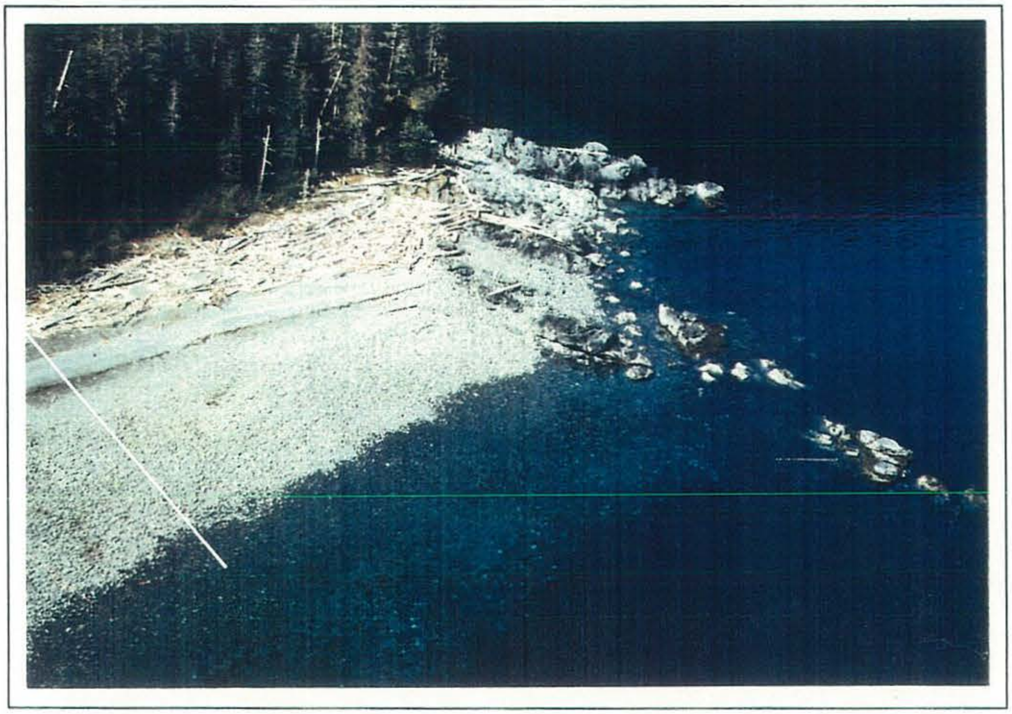
   This part of the profile, a continuation of the highly armored uplifted platform, slopes seaward at a smaller angle (3°) than the upper platform. No changes occurred on this section of the beach during the study period. Barnacles, mussels, and *Fucus* occur at the lower levels, but not in the profusion seen on the profiles discussed earlier.

FIGURE 46. (Facing Page) Photos of station N-7.

A. Oblique aerial view of station looking west on 25 May 1990. Line shows approximate location of the profile. The accumulation of gravel against the rocks is an indication of westerly sediment transport (natural groin effect). Note projection of armored platform underwater. Photo by M. Hayes.

B. Ground view to west from a few meters below the last high-tide swash line on 25 May 1990. This is near the beginning of the armored zone. Photo by M. Hayes.

A.



B.

This profile at station N-7 was surveyed 7 times (see Table 4). Except for the 4 December 1989 survey, when a horizontal reading error of approximately 1 m was recorded, there were no major errors in the fall and winter survey data that we could detect. A new front stake was established on 2 January 1990 and never tied to the original back stake on the field note sheets, but, fortunately, this was done during the 25 May 1990 survey.

This station showed only minor changes during the survey period, as shown by the overlay profile plots in Figure 48. In their report to NOAA on the fall and winter surveys, Sexton, Gibeaut, and Balcom (1990) state that the profile changes between September 1989 and February 1990 were "one of erosion across the entire profile". We believe, however, that this deduction is a result of the reading error in the 4 December 1989 survey. There was deposition of a high spring berm at the 12 m mark after the mid-October high spring tides (Fig. 48A). Only minor changes, mostly in the berm area, occurred between the 18 October 1989 and 2 January 1990 surveys (Fig. 48B), and the same can be said for the interval between the 2 January 1990 and 25 May 1990 surveys (Fig. 48C). The deviations of the plots for the last two surveys shown (Fig. 48C) on the lower platform is probably brought about by the irregular nature of the boulder-strewn surface. Michel comments in the field notes for the 6 September 1990 survey that there had been "no change from May".

It is evident from the profile data and the relatively poor sorting and subangular and subrounded character of the gravel (Fig. 48A) that significant sediment motion on this profile is restricted to major storms. The well-developed storm berm on the profile is evidence of major sediment movement at least every few years, because the berm must be less than 25 years old. A sediment envelope of a maximum of only 20-30 cm was developed on this profile during the study period as a result of spring berm growth and migration. The sediment transport direction on this beach is east to west, as evidenced by the natural groin effect just west of the profile (Fig. 46A).

Sediments. The sediments on this beach were derived from wave erosion of the adjacent bedrock headlands. According to Moffit (1954; p. 267), the bedrock of this part of Knight Island "is made up of greenstone that is in part intrusive and in part extrusive", plus minor occurrences of shale and graywacke. When we conducted our sediment texture studies on this beach on 24 June 1990, we noted that the clasts were mostly fine-grained mafic igneous rocks plus a few diorites, which is in agreement with Moffit's statement.

The surface sediment distribution along the profile was estimated at 18 sites during the 25 May 1990 survey. The results, which are illustrated in Figure 45C, show that: 1) the storm berm face was covered with pebbles; 2) the spring berm surface was mostly cobbles; 3) boulders increased up to 40 percent of the total in a seaward direction across the upper platform; and 4) the same trend continued across the upper half of the lower platform, with boulders decreasing to 20 percent on the lower half. Overall, the sediments are finer-grained and not so well-sorted as those at stations N-1, N-3, and N-4, though the same general fine-to-coarse trend in the offshore direction is present. The increase in fines at the toe of the lower platform is probably because that area is below the zone of peak wave-generated currents and turbulence at high tide.

On 24 June 1990, a detailed study was conducted on the clasts at 6 sites along the profile, using the same methods described for station N-1. The trend of (L+I)/2 for all the surface clasts measured at the six sites is given in Figure 49. A clear offshore coarsening is shown. Measurements of (L+I+S)/3 were made of surface and immediately underlying layers at the sites, with the following results (measurements in cm):

	15 m	30 m	45 m
surface layer	11.6	17.5	19.1
first underlying layer	2.0	5.4	2.9

FIGURE 47. (Facing Page) Additional photos of station N-7.

A. Oil coat and stain on the surface cobbles of the upper part of the upper platform on 8 December 1990. Note angularity of cobbles compared with stations described earlier. Photo by J. Michel.

B. Trench dug on lower platform on 8 December 1990. Oil sheen and mousse has accumulated on the water table. A sample at 15 cm contained about 4,000 ppm TPH. Note fine nature of substrate, which contains abundant sand and granules in comparison with the coarse surface armor. Photo by J. Michel.

A.

B.

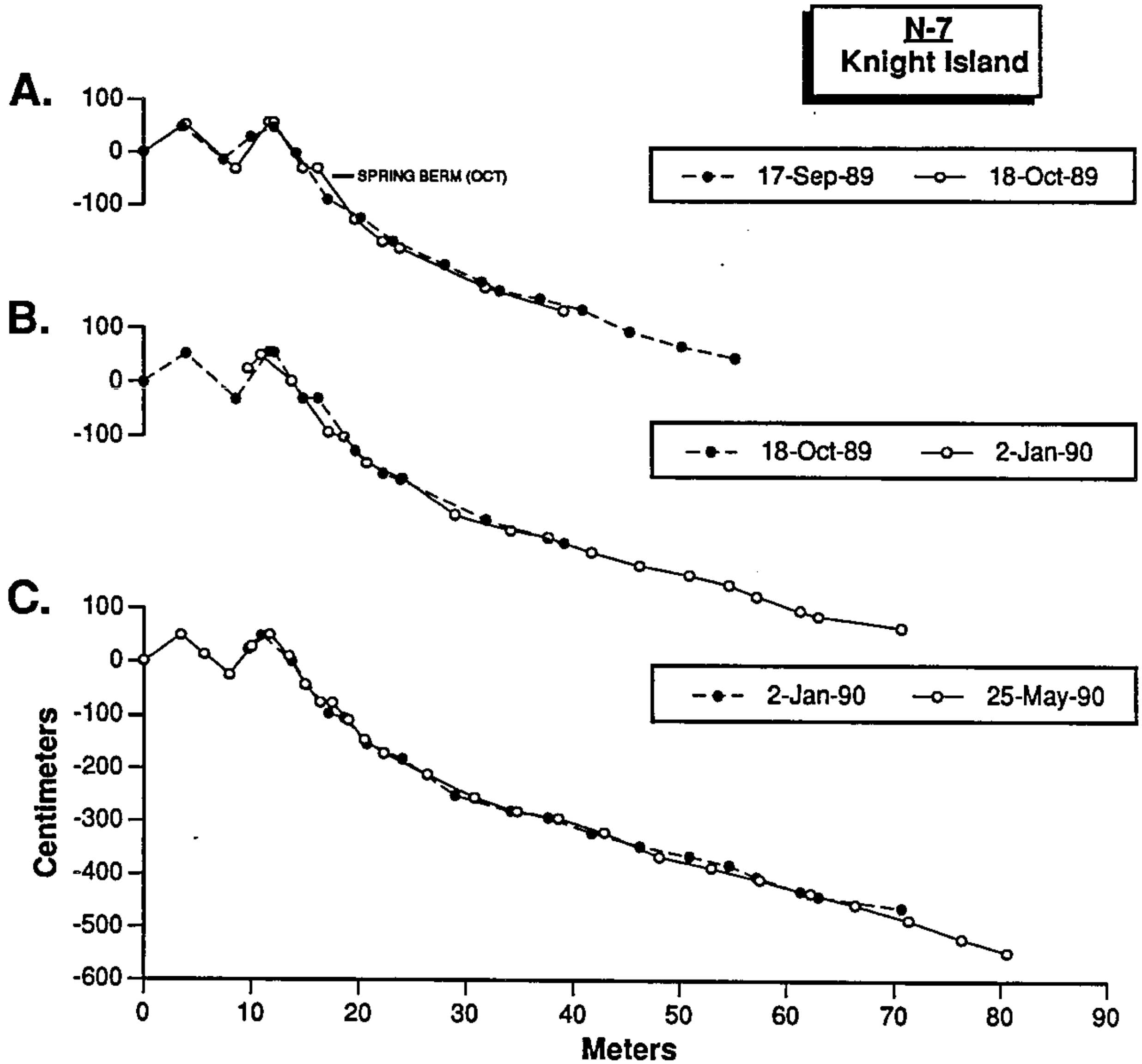


FIGURE 48. Sequential beach profiles at station N-7, showing the relative lack of major changes of this profile during the study period.

A. (17 September 1989 and 18 October 1989) A spring berm was built during the high spring tides of mid-October.

B. (18 October 1989 and 2 January 1990) The only changes were minor changes in the berms on the beachface of the storm berm.

C. (2 January 1990 and 25 May 1990) Again, no major changes during this time interval.

Forty clasts on the surface of the upper and lower platforms were compared with the roundness chart in Figure 19 and a value of 3.5, or middle of subrounded class, was obtained. There was a wide range of roundness values exhibited by the clasts, with many ranging well down into the subangular category. It is probable that the better rounded clasts are inherited from the pre-earthquake beach.

A total of 22 trenches were dug on this profile during the study. Those dug on 25 May 1990 are described in Figure 50. All of the trenches dug on the upper and lower platforms showed excellent armoring, with the surface layer ranging up to 50 percent boulders and the combined lower layers containing around 50 percent sand, no boulders and only a few cobbles and pebbles. This is clearly demonstrated by trenches D and E on 25 May 1990 (Fig. 50).

Oil Distribution Patterns. The more sheltered nature of this site was well reflected in the oil distribution patterns. From September through December 1989, the upper third of the beach surface was 45-100 percent covered by oil (Figs. 51 and 47A). The oiling at the high-tide berms was consistently described as fresh-looking oil. In the January and February 1990 surveys, the oil had weathered to a dark stain or coat covering 40 percent of the larger cobbles. This oil was not being removed from the irregular surface of the cobbles. Little to no visible oil was observed on the lower platform surface sediments. By May 1990, the remaining surface oil consisted of a 5 percent coverage, occurring as a coat in the irregular depressions on the cobbles. This coating was very persistent; there was no change in the September 1990 surface oil distribution (Fig. 51).

The TPH results of surface sediment samples collected from this station (Table 9) reflect the low surface oil distribution on the upper beach area and are surprisingly consistent. The surface sediments at this station were collected at the contact between the overlying cobble/boulder armor and the finer-grained substrate. Thus, the samples were much more uniform in grain size than, for example, at Pt. Helen, although they were still very heterogeneous. They contained more than 50 percent pebble, granule, and sand, thus both the original oil distribution and the representativeness of samples is more uniform. Most samples from the berms were in the 200-400 ppm range, showing perhaps effects from transport and cleaning of the pebble fraction during the hot-water flushing, and showed little change over time. Two samples collected in September 1989 from the upper platform samples had 1,450 and 6,600 ppm oil, the highest of any surface sediment samples collected from the active beach on this shoreline type. These samples were collected from the lower part of the upper platform, which was estimated to have 70 percent oil coverage on the cobbles and pebbles. Heavy surface oil remained on this shoreline through September, indicating its lower wave energy and the large reservoir of subsurface oil which could re-oil the surface. (Remember, fresh oil was observed during the fall/winter 1989.) Subsequent samples were collected higher in the zone and had consistently lower TPH levels. But re-oiling apparently continued to be a source for surface contamination, keeping oil levels at 300-500 ppm at the high-tide level. The lower platform surface sediments appeared to be clean throughout our surveys.

The subsurface sediments at this site were heavily contaminated throughout the period of our survey, even through September 1990. Reoiling and reworking of the pebble high-tide berms caused large variations in the oil content of the upper 25 cm. The deeper samples were always collected at 45-50 cm depth, at what could be visually determined to be the base of the oiled zone. These results are quite consistent, ranging between 340 and 390 ppm. By September 1990, no oil was visible in the top 25 cm of the pebble berm, and only a light oil sheen was observed with depth. Erosion and deposition of the berms will continue to lower oil levels in these sediments.

There is no known sediment reworking mechanism available for removal of subsurface oil from beneath the large and stable armor of the upper and lower platforms, short of extreme turbulence generated by a major storm. Pebbles, granules, and sand make up 80 percent of the sediments below the armor (Fig. 47B), and thus the sediments are much finer-grained than previous stations discussed in this class of raised platforms. Bedrock was never exposed or reached in trenches, so it is greater than 1 m deep all along the profile. There is no source of freshwater runoff from the upland. All these factors contribute to slow tidal flushing of oil from the subsurface—the only other possible physical mechanism for oil removal from the subsurface. The TPH measurements of subsurface sediments from the platforms in Table 9 show little change in oil over time. The deeper samples from the upper platform were all collected at about 40 cm depth, and ranged from 8430 to 9800 ppm over three sampling periods. The shallower zone showed more variation, from 983 ppm in October 1989 to 13,090 ppm, the highest value measured at this station, in February 1990. The lower platform, the flattest of any station in the category (3°), was also heavily oiled, down to a distance of at least 50 m from the spring high-tide line (Fig. 47B).

TPH concentrations were consistently in the 11,000-13,000 ppm range for the upper 35 cm. Oil extended to almost 45 cm; below this depth the sediments appeared clean. The data in Table 9 for the deep samples from the lower platform are for sediments at 40-45 cm, with TPH levels at 400-1,200 ppm. The subsurface oil sheened readily.

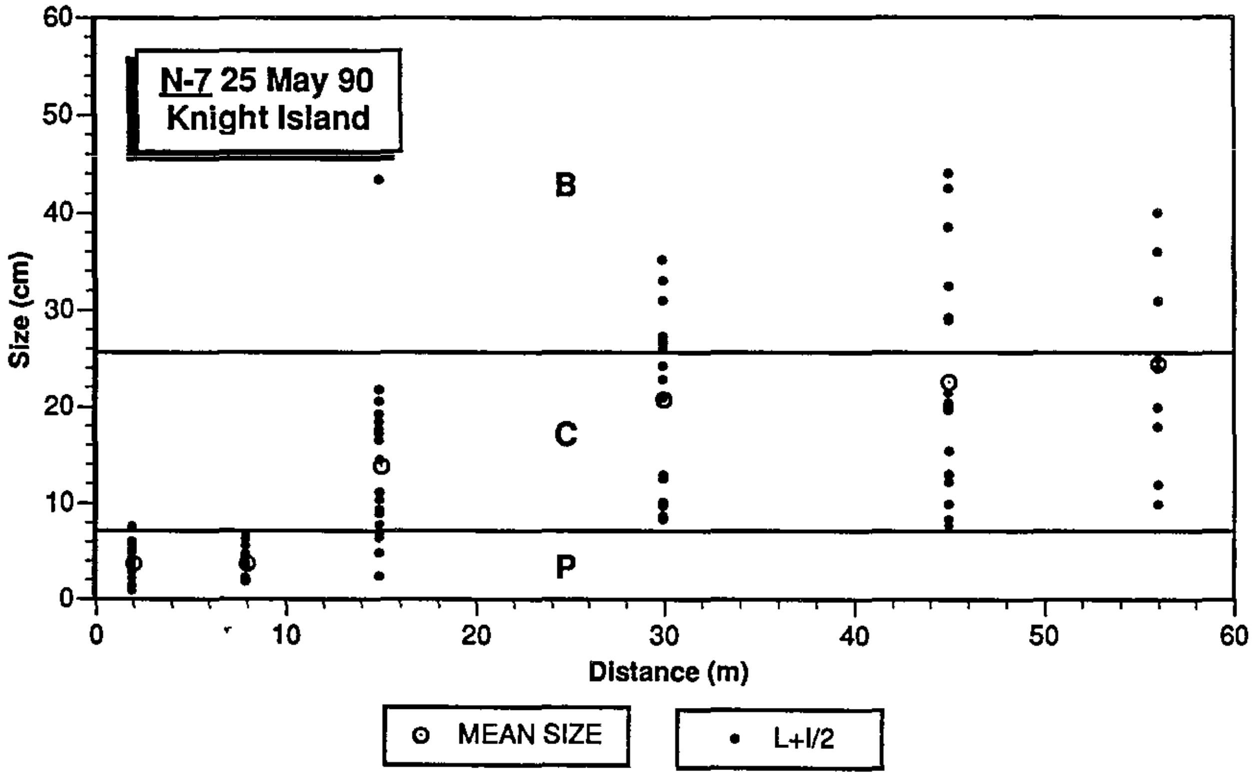
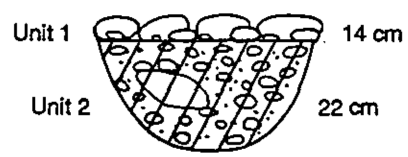


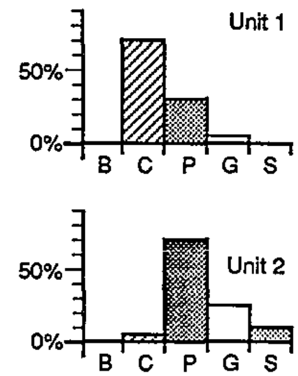
FIGURE 49. Plot of (L+I)/2 for all the surficial clasts measured at 6 sites on profile N-7. Note consistent increase in size in an offshore direction.

N-7 KNIGHT ISLAND NE, 25 MAY 1990

- Oiled Zone

TRENCH A

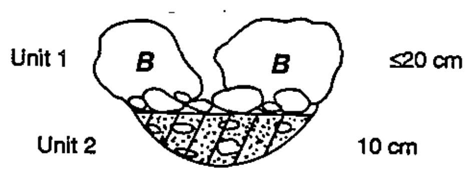


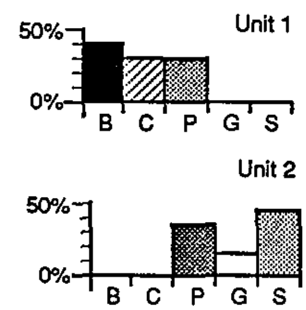


Unit 1: 5-10% residual stain

Unit 2: Heavily stained; no mobile coating
Strong hydrocarbon smell

TRENCH D

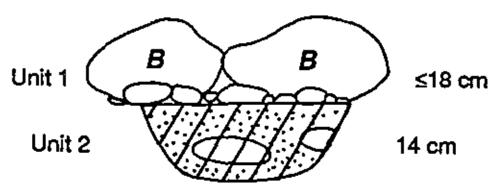


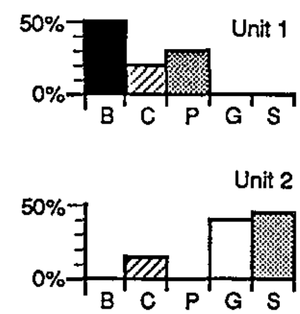


Unit 1: <1% residual stain

Unit 2: Mousse coating, medium brown
Pores not filled

TRENCH E





Unit 2: Thin mousse film, medium brown

(NOTE: NO TRENCHES B & C)

FIGURE 50. Description of three of the trenches at station N-7 on 25 May 1990. See Figure 45B for location. A superbly armored surface occurred at trenches D and E, both of which were dug on the lower platform. Note abundance of sand and granules in the lower layer.

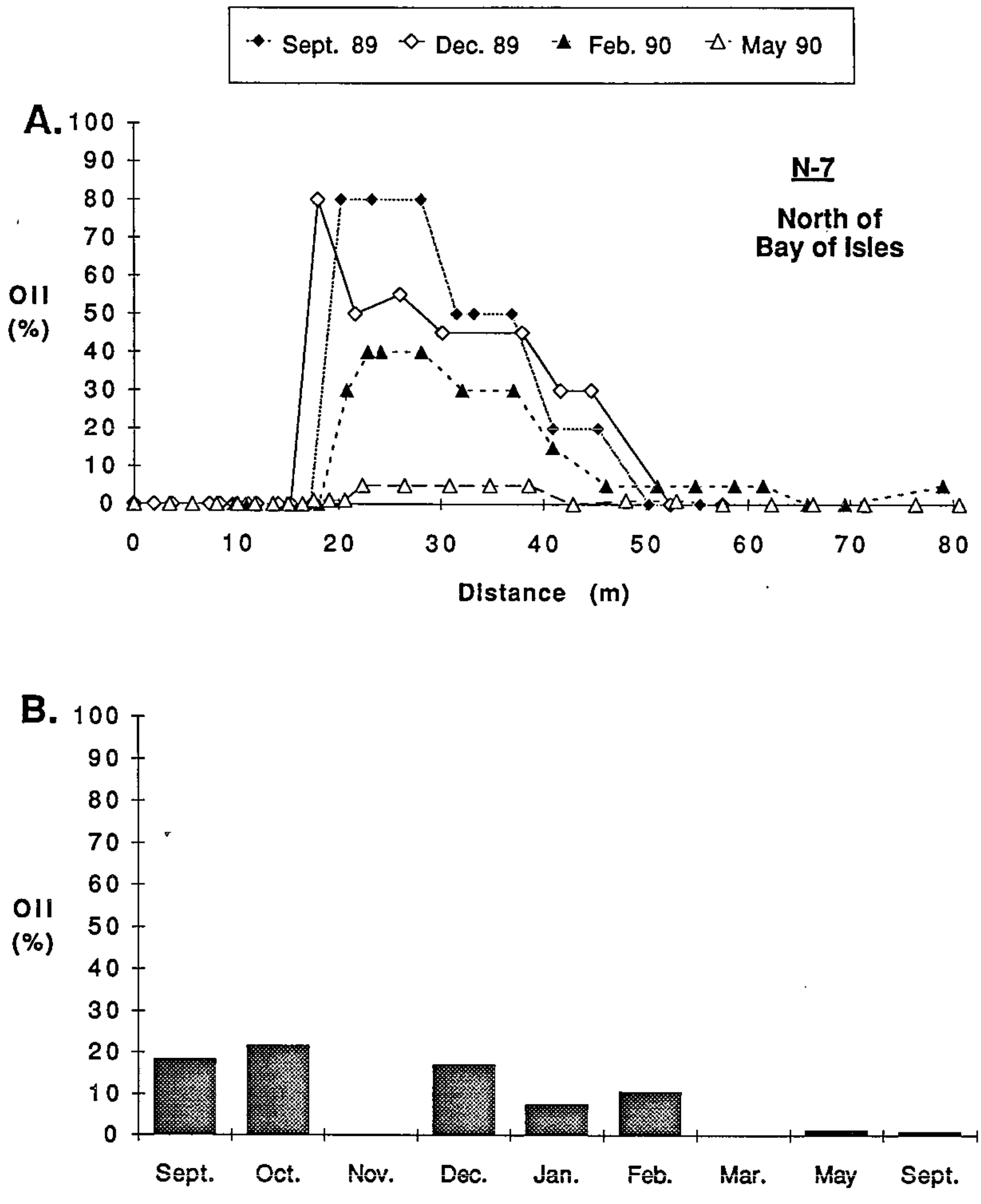


FIGURE 51. Plots of percent coverage of surface oil along profile N-7.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 9. Sediment TPH (in ppm) for N-7 on Knight Island by morphological zone.

Surface Samples

Date	High-Tide Berms	Upper Platform	Lower Platform	Mean
9/89	399/760	1,450/6,600		2,300
10/89	40/100	340		150
12/89	340	310	40	230
1/90	360	220	30	200
2/90	470			

Subsurface Samples

Date	High-Tide Berms < 25 cm	High-Tide Berms > 25 cm	Upper Platform < 25 cm	Upper Platform > 25 cm	Lower Platform < 35 cm	Lower Platform > 35 cm
9/89	6,610		3,030			
10/89			980		12,780	
12/89	590	340	1,240	9,800	4,040	
1/90		390		8,820	11,070	430
2/90	5,080	370	13,090	8,430	11,380	1,220

These results are similar to the TPH data for sediment samples collected as part of the bioremediation monitoring study at this station. TPH concentrations of 14,000-25,000 milligrams per kilogram (mg/kg), which are the same as the ppm by weight we have reported in Table 9, were measured for 13 subsurface samples collected in late May 1990 (Prince, Clark, and Lindstrom, 1990). The fertilized section of the platforms showed a steady decrease in TPH levels in subsurface sediments, from a mean of about 22,500 mg/kg to a mean of about 15,000 mg/kg 61 days later. The untreated section of the platforms went from a mean of about 18,500 mg/kg to about 15,250 mg/kg over the same period.

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

Station N-15

Introduction. Station N-15 is located near the middle of a northwest-southeast oriented, 250 m long pocket beach on the northeast corner of Latouche Island (Fig. 16). This is a highly exposed location for PWS. The effective fetch perpendicular to the beach is around 25 km, but to the north-northeast (70° angle to the beach), the effective fetch extends to 40 km. In a due easterly direction (35° angle to the beach), the effective fetch is decreased to 15 km, because of the sheltering effect of Montague Island. The uplift of this site was around 3.5 m during the 1964 earthquake, the greatest at any of the 18 permanent monitoring sites. This station has what we interpret to be a raised shore platform as it's underpinning, but there are no exposed bedrock outcrops along the platform. Instead, a highly oxidized, compact sediment mixture underlies the mobile sediment on the platform surface. The tectonic history of Latouche Island is quite complex and we have much to learn about it, thus this interpretation may be incorrect. A field sketch, beach profile, and sediment distribution plot for the profile on 26 May 1990 are given in Figure 52 and selected photographs are presented in Figures 53, 54, and 55.

The shoreline was heavily oiled in March 1989. Being near the southern extent of oil in PWS, cleanup crews did not work this segment at all until late August/September 1989. Apparently, the area received a quick hot-water wash then an application of Inipol. The treatment must have been very cursory; we established our station on 19 September 1989 and noted that it was a set-aside site. In reality, the set-aside site was the next pocket beach to the south. The oiled cobbles were very slippery and glistening at the time of the first survey (Fig. 54A), indicating a recent Inipol application. There was no evidence of much other treatment at the site.

N-15 25 June 90
Latouche Island

A.

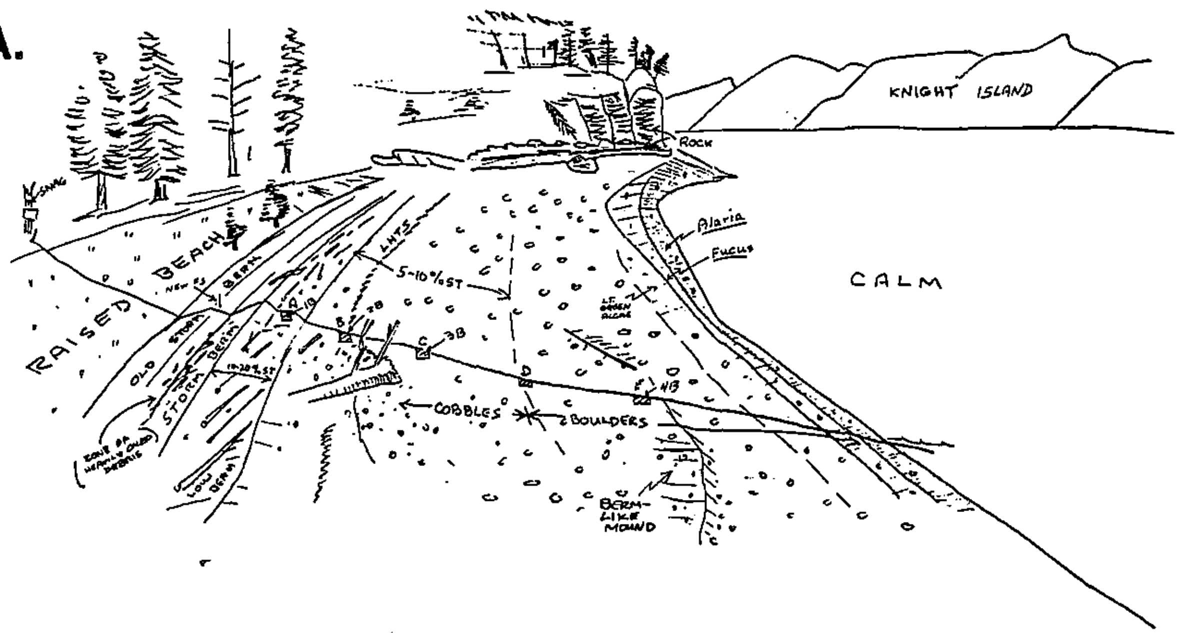
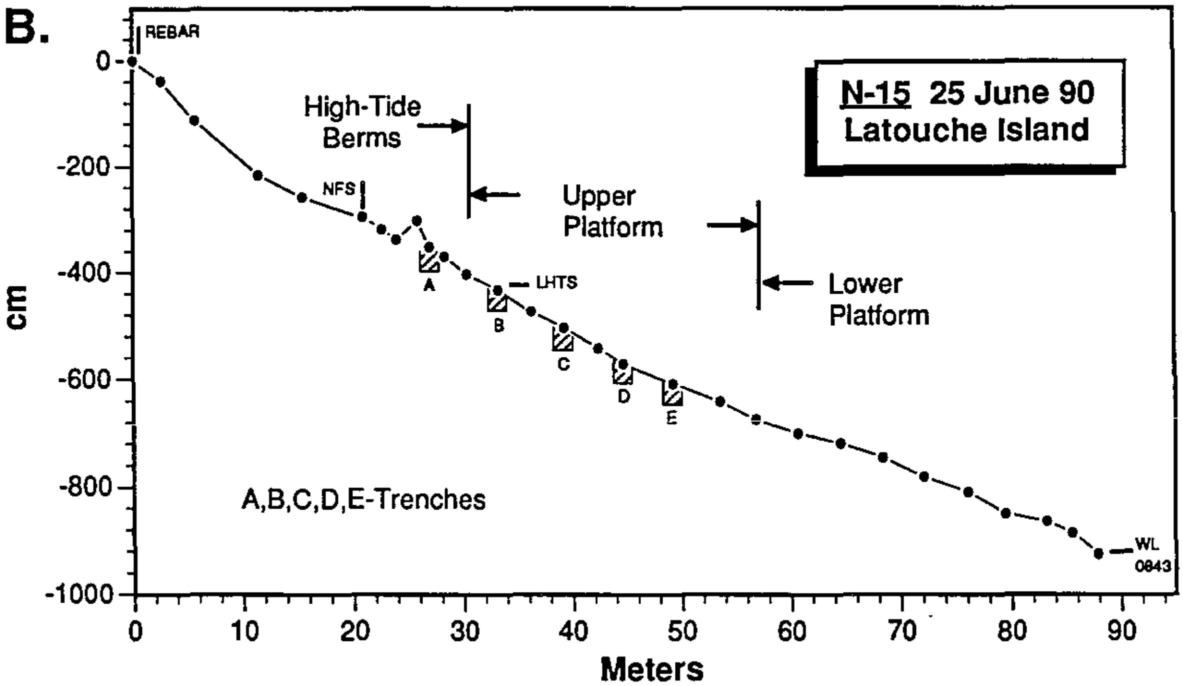


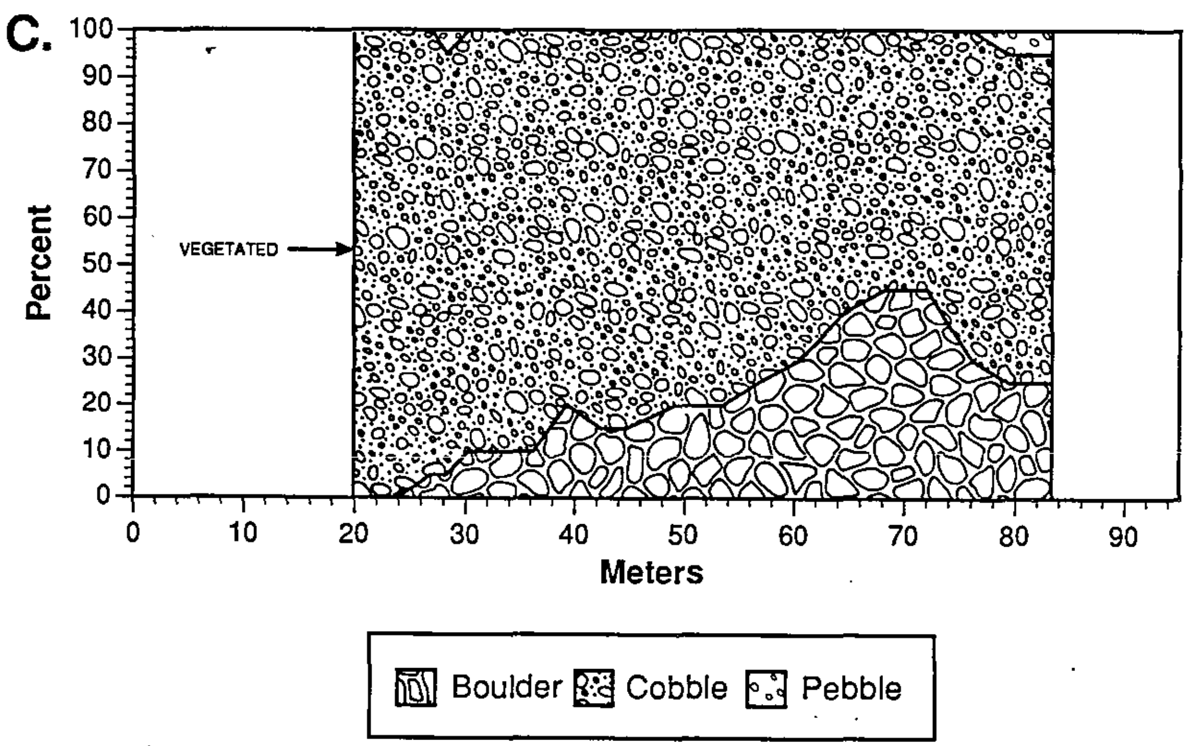
FIGURE 52. Station N-15 on 25 May 1990.

A. Field sketch. Note presence of "old" and new storm berms and near absence of secondary berms. The high part of the berm-like ridge in the foreground was on the profile during the 1 February 1990 survey.

B. Topographic profile demonstrating the three primary components—high-tide berms, upper platform, and lower platform.

C. Distribution of surface sediments along the profile, based on estimates made at the 23 survey sites indicated by circles (in diagram B). Note near absence of pebbles and the general increase in boulders in an offshore direction.


B.
REBAR
N-15 25 June 90
Latouche Island
High-Tide Berms
Upper Platform
Lower Platform
NFS
LHTS
A
B
C
D
E
WL
0843
A,B,C,D,E-Trenches
cm
0
-200
-400
-600
-800
-1000
0
10
20
30
40
50
60
70
80
90
Meters


C.
Percent
100
90
80
70
60
50
40
30
20
10
0
VEGETATED
0
10
20
30
40
50
60
70
80
90
Meters
Boulder
Cobble
Pebble

In 1990, no work was conducted on this site until early September; during our visit on 5 September, crews were conducting a "berm relocation". Our profile was run right through the area of active excavation, which extended down to the red oxidized zone. Excavated sediments had been piled on top of the upper platform, covering a zone about 25 m wide. After tidal flushing of the exposed sediments, they were pushed back into the original position and Inipol/Customblen were applied. This "berm relocation" actually consisted of tilling of the middle part of the beach, wholesale excavation of the entire upper beach, placement of this material throughout the middle intertidal zone for tilling and tidal flushing, and then replacement. A small tracked bobcat was used for all transport of sediment and filling of the excavated sediment. Between each high tide, the bobcat would "till" the pile of sediments, attempting to turn over the pile and expose more oiled sediments to the surface. None of the original substrate in this middle zone was manually disturbed. This type of berm relocation is disruptive of the upper and parts of the middle intertidal zone. However, the station is very exposed to the predominant storm waves, so the sediments may be reworked into their original distribution over the storm season. Evaluating the sediment and biological recovery will be part of on-going surveys. Exxon reviewers of this report state that "the berm relocation program was designed to avoid relocation of oiled material or sediments to the lower intertidal areas and other sections of the intertidal zone which were either armored or had abundant biota. In most cases, the design was carried out well and no other problems were encountered." (John Wilkenson; letter dated 25 January 1991).

Morphology and Beach Dynamics. In addition to the seasonal monitoring studies at station N-15, the study area was expanded on 25 June 1990 to include two adjacent profiles, N-15X, located 70 m to the northwest of N-15, and N-15Y, located 67 m to the southeast of N-15. A sketch map of the entire 250 m long pocket beach area is given in Figure 56. Profiles and sediment distribution patterns for profiles N-15X and N-15Y are given in Figures 57 and 58, and a three-dimensional plot of the beach area encompassed by the three profiles is given in Figure 59. These three profiles, like the ones previously discussed, can be subdivided into three morphological components:

1) High-tide berms

Despite the fact that the raised storm berm at this site is quite large (see sketch in Fig. 56), the post-1964 storm berms on these profiles are rather small, reaching a maximum height of only 35 cm at profile N-15X (Fig. 57). The storm berm at N-15 was slightly erosional most of the time and no major spring berms were encountered on the profile. A well-developed spring berm was present at both station N-15X and station N-15Y on 25 June 1990 (Figs. 56, 57, and 58). The average beachface slope of the high-tide berms at the three profiles was 15°.

2) Upper platform

This surface, which dips seaward at 5° on profile N-15X, 6° on profile N-15, and 5° on profile N-15Y, was relatively featureless most of the time at station N-15 and showed very little change. Berm-like ridges were found on some parts of the upper platform on 25 June 1990 (Fig. 56). A highly armored surface of cobbles covers the upper platform.

3) Lower platform

This surface dips seaward at a slightly smaller angle than the upper platform (N-15X = 4.5°; N-15 = 4°; N-15Y = 4°). There are more boulders in the surface sediments, which decrease in abundance in a southeasterly direction. Berm-like ridges are common throughout the area (Fig. 56). Heavy growth of Fucus and Alaria algae occur on the lower reaches of this zone.

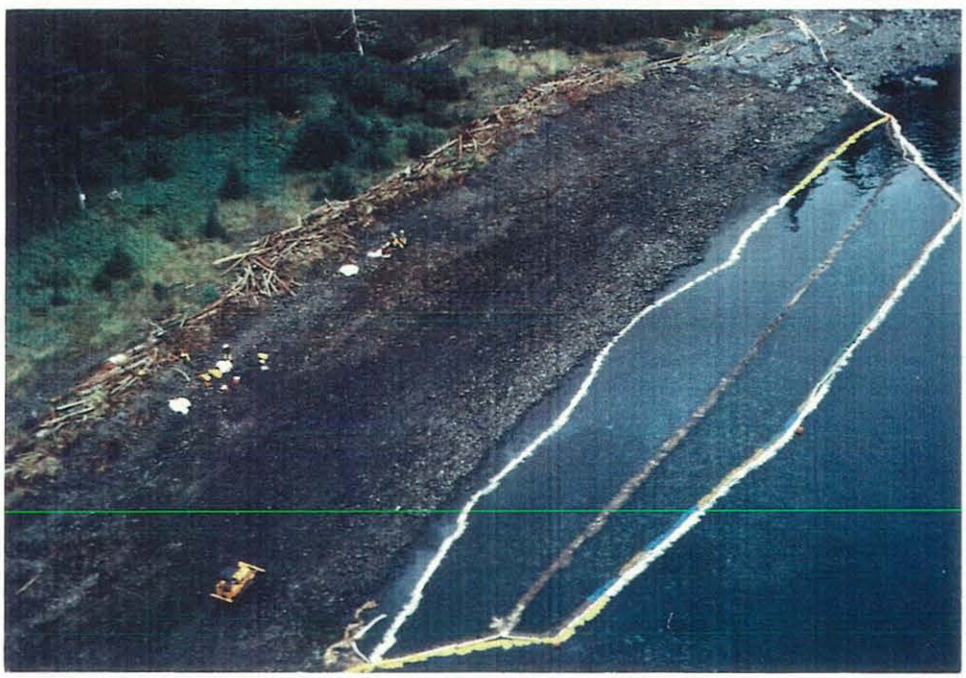
FIGURE 53. (Facing Page) Photos of station N-15.

A. View looking northwest of the pocket beach at station N-15 on 26 May 1990. Line shows location of the profile (N-15). Note faint berm-like ridges on the middle of the raised plat-form, and the accumulation of gravel on the updrift (north-west) side of the large log (arrow). Photo by M. Hayes.

B. Similar aerial view as the one shown in A on 5 September 1990. Berm relocation activities were in progress on this date. Note abundance of exhumed oil. Photo by J. Michel.

A.

B.



The beach profile at station N-15 was surveyed eight times. All surveys, except those run on 20 October 1989 and 4 January 1990, show almost total overlap of the profiles run on 19 September 1989 and 26 May 1990. We conclude, therefore, that the 20 October 1989 and the 4 January 1990 profiles were not run along the same bearing as the others. Notes on the 20 October 1989 field sheet read "today's transect does not appear perpendicular to water line". No front stake was established until the 26 May 1990 survey. Except for those two surveys, however, the data appear to be remarkably free of aberrations. Except for a "small rise" on the lower portion of the upper platform and the single low-level storm berm, profile N-15 was quite featureless on 19 September 1989 (see overlay plots in Fig. 60A). There appeared to be an elevation and landward retreat of the storm berm (a few cm) some time between the 19 September 1989 and 6 November 1989 surveys. There was very little change between the 6 November 1989 and 5 December 1989 surveys (Fig. 60B). The first appearance of berm-like ridges* was noted at the 37 m mark during the December survey. In the notes for that survey, Gibeaut noted that a layer of "very large cobbles and small boulders" overlaid a "consolidated matrix of granules and larger" on the top of the berm-like ridge. He noted further that the "interface" was distinct and that the "wet" lower layer supported an abundant biota made up of barnacles, mussels, and grammarid amphipods.

The upper one-third of the profile was covered with a thick layer of snow during the 1 February 1990 survey. The only discernible change between the 5 December 1989 and 1 February 1990 surveys was the appearance of a new, 30-cm high berm-like ridge on the lower platform (Fig. 60C). No changes occurred between the 1 February 1990 and 26 May 1990 surveys, except for the lowering of the profile on the lower platform by May (Fig. 60D). This change was probably brought about by the southeasterly migration of the ridge. A smaller remnant of the ridge was still present on the profile on 26 May 1990 (Fig. 52B) and the larger component of the ridge is visible to the southeast of the profile in the field sketch (Fig. 52A).

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* In the field notes, terms such as "small rise", "lower berm", and "berm" were used to describe these features we now call berm-like ridges.

As seen by the comparative profile and field sketch for the 5 September 1990 survey given in Figure 61, a major berm relocation was initiated on this profile in early September 1990. The sediment was excavated down to a red-stained, oxidized substrate, which obviously overlies the bedrock of the raised platform. The excavated material, which extended all the way to the low water level at the time of the survey (Fig. 61), was apparently piled on top of the armored surface of the upper platform. In the field notes, Michel noted that the surface of this excavated material was "totally devoid of life".

FIGURE 54. (Facing Page) Additional photos of station N-15.

A. Heavily oiled surficial cobbles and boulders of the upper platform on 19 September 1989. Photo by J. Michel.

B. Partially cleaned surficial cobbles on the lower platform on 20 October 1989 only one month later than when the photograph in A was taken. Note excellent roundness of the clasts. Photo by D. Hall.

A.

B.

The potential for sediment mobilization along the upper and lower platforms is significant, as seen by the presence of numerous berm-like ridges (Figs. 52B, 56, and 60D). These ridges, however, were not observed to create a sediment envelope greater than 30 cm thick. Spring berms were present at profiles N-15X and N-15Y on 25 June 1990, which probably accounted for sediment envelopes on the order of 50-60 cm thick during the study period. But, as noted above, there was very little vertical change at the high-tide berm level of station N-15 over the study period. In fact, the zone around profile N-15 seems to be a focus for erosion on the profile, as revealed by the sketch map in Figure 56.

Several lines of evidence indicate that the dominant sediment transport direction on this beach is northwest to southeast:

1) There is a general decrease in grain size in that direction (compare Figs. 52C, 57B, and 58B).

2) The berm-like ridges are oriented obliquely to the beach, indicating transport to the southeast (Fig. 56).

3) The individual clasts become more rounded in a southeasterly direction.

4) The sediment is piled up against the north side of the large log southeast of profile N-15 (shown in Fig. 53A). The spring tide berm at profile N-15Y is oriented toward the dominant northerly waves (Fig. 56).

Sediments. Most of the clasts on this beach are derived locally from erosion of the bedrock headlands to the northwest of the site. A small stream deposits some gravel on the southeast corner of the beach (Fig. 56). According to Moffit (1954), the bulk of the bedrock on this part of Latouche Island is interbedded slates, argillites, and graywackes, which is the composition we found during our studies of clast size and shape on this beach.

The results of our detailed studies of surface sediment distribution along the three profiles are presented in Figures 52C, 57B, and 58B. The grain-size estimates were made on 26 May 1990 on profile N-15 and on 25 June 1990 on profiles N-15X and N-15Y. Surface sediments were coarsest on profile N-15X, which is located closest to the primary source. On profile N-15X, pebbles make up around 70 percent of the surface sediments of the high-tide berms, cobbles dominate the upper platform, and boulders make up around 60 percent of the surface sediments of the lower platform. There were two subtle berm-like ridges on the lower platform of station N-15X on 25 June 1990, and in both cases, boulders were more abundant on the crests of the ridges than in the troughs between them (Fig. 57). On profile N-15, surface sediments are almost entirely cobbles in the high-tide berms area; cobbles make up more than 80 percent of the sediments on the surface of the upper platform, the rest being boulders; and boulders cover 30-40 percent of the surface of the lower platform. Pebbles were extremely scarce on station N-15 on 26 May 1990 (Fig. 52C), which is probably accounted for by the absence of a spring berm on the profile, as well as an erosional zone being focused in the center of the beach (Fig. 56). On station N-15Y, pebbles again dominate the high-tide berms; cobbles make up more than 50 percent of the surface sediments of the upper platform, with boulders increasing to 20 percent at the juncture with the lower platform. Pebbles, cobbles, and boulders are roughly equally represented on the lower platform of profile N-15Y. The two berm-like ridges present on the lower platform profoundly influence the grain size distribution, with coarsest material occurring on top of the ridges and finest in the intervening swales (Fig. 59B). The abundance of pebbles on the lower platform is probably the result of two influences: 1) distance from primary source; and 2) presence of stream on that part of the beach.

On 25 June 1990, detailed measurements of size and roundness of clasts were carried out at 5 sites on profile N-15X, 6 sites on profile N-15, and 6 sites on profile N-15Y. To show details of that data on clast size in this report would be somewhat redundant because the trends closely mimic the results of the estimates of surficial grain size given in Figures 52C, 57B, and 58B. With regard to roundness, however, for 80 clasts measured on profile N-15X the ρ value was 4.0 (boundary between subrounded and rounded), for 100 clasts measured on profile N-15 the ρ value was 4.8 (high in roundness class), and for 90 clasts on profile N-15Y the ρ value was 5.0 (boundary between rounded and well rounded).

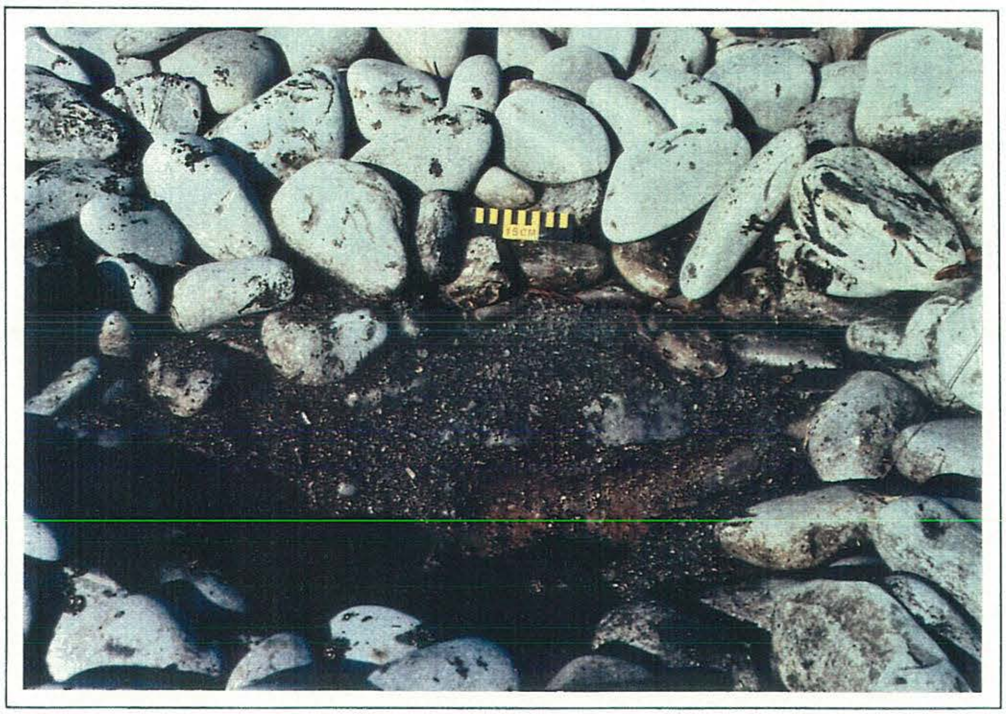
FIGURE 55. (Facing Page) Additional photos of station N-15.

A. Trench on upper part of lower platform on 20 October 1989. Oil shown on cobbles by scale is true representation of surface oil, whereas those cobbles in the middle right have been turned over in the process of digging the trench. Photo by D. Hall.

B. Trench C in the middle of the upper platform on 26 May 1990. Surface cobbles were relatively clean on this date. Photo by M. Hayes.

A.

B.



A total of 24 trenches were dug on profile N-15 during the study. Figure 62 illustrates the four trenches dug on 26 May 1990. All four of these trenches, which were dug on the upper platform, show superb surface armoring, primarily by cobbles.

Oil Distribution Patterns. The plots in Figure 63 show a very gradual decrease in the surface oil coverage between September and December 1989. What the plots do not show is the large decrease in the thickness of the oil coating. In September 1989, the 100 percent oil coating on the berm and upper platform was thick and very sticky (Fig. 54A). Each cobble was completely covered all around, and all the cobbles in the surface layer were oiled. By the October survey, the oil coating was described as a sticky thin layer. By November, it was described as a tacky stain, but still 70-80 percent coverage. Therefore, the total amount of surface oil at this station decreased significantly, although the coverage plots show much less change (compare Figs. 54A and 54D). By May 1990, much of the oil had been removed from the cobble layer, down to 2-3 cobbles deep (Fig. 55B). The October 1989 high tides did overtop the active storm berm, and a large amount of oily debris was stranded behind the berm, under piles of logs. The spike of heavy surface oil shown in December 1989 (Fig. 63A) is covered by snow in February 1990. This oiled debris persisted until cleanup work in September 1990. Because the surface sediments are composed of a cobble veneer, samples for TPH analysis are of limited value. The upward spike in the September 1990 data (Fig. 63B) is the expected result of sediments exposed by berm relocation.

The subsurface sediments were defined as beginning at the base of the layer of cobble/boulder armor (shown in Fig. 62). The subsurface sediments were a tightly packed mixture of mostly pebbles with cobbles and granules. These sediments were totally immobilized beneath the cobble/boulder armor, and the heavy oiling tended to increase the immobility. Cobbles partially buried in the sediments were difficult to pry loose, with the oil making a tight seal (Fig. 55A).

The oil content of these subsurface sediments was very high, ranging up to 48,300 ppm, or 10.5 percent by volume. The oiled zone was very well defined, both areally and with depth, and it extended seaward for about 25 m along the profile. All trenches shown in the sketch in Figure 59A contained oiled substrate, though trench E has only a thin brown film (Fig. 62). The depth of penetration was limited by the impermeable oxidized layer at 25 cm below the cobbles (trench C; Fig. 62). In fact, the presence of this impermeable layer was one reason for the very high oil levels. At other sites, such as N-7, the oil penetrated down deeper, usually more than 25 cm, the depth controlled by the water table, amount of oil pooled on the surface, and/or the permeability of the substrate. The impermeable zone at N-15 tended to concentrate the oil in the top layer. The range of values in Table 10 is driven more by whether the sample contained a small cobble or two, than by any variation in overall oil content of the finer grained material. The subsurface was uniformly heavily oiled and showed no change over time. There was little flushing of the sediment by tidal action, and no physical reworking of the sediments. That is, until early September 1990, when the entire berm and upper platform were completely relocated (Figs. 53B and 61). The sediments were excavated down to the oxidized layer, and piled seaward to be flushed by tidal action. Sorbent booms were placed to pick up the freed oil. After a few tidal cycles, the sediment was placed back into the excavation area. It will be extremely interesting to study the redistribution of the oil and sediments - we are fortunate to have established multiple profiles and a map of the sediment distribution. Monitoring of this station will allow us to better understand the rate of recovery of such highly disturbed sediments and the effectiveness of mixing on the persistence of the subsurface oil.

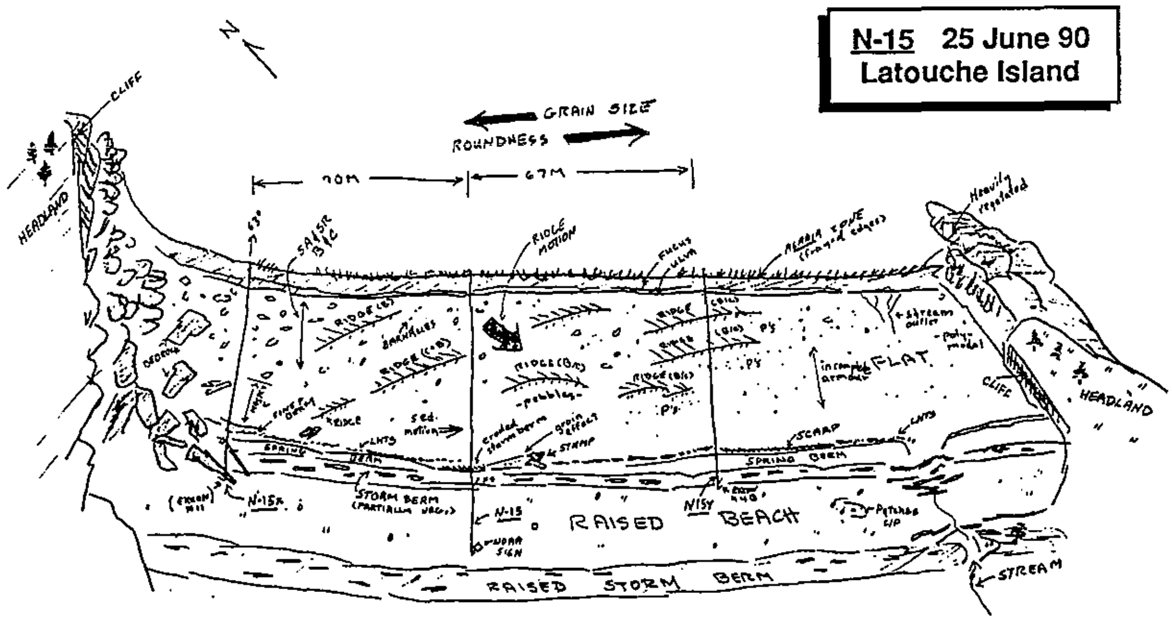
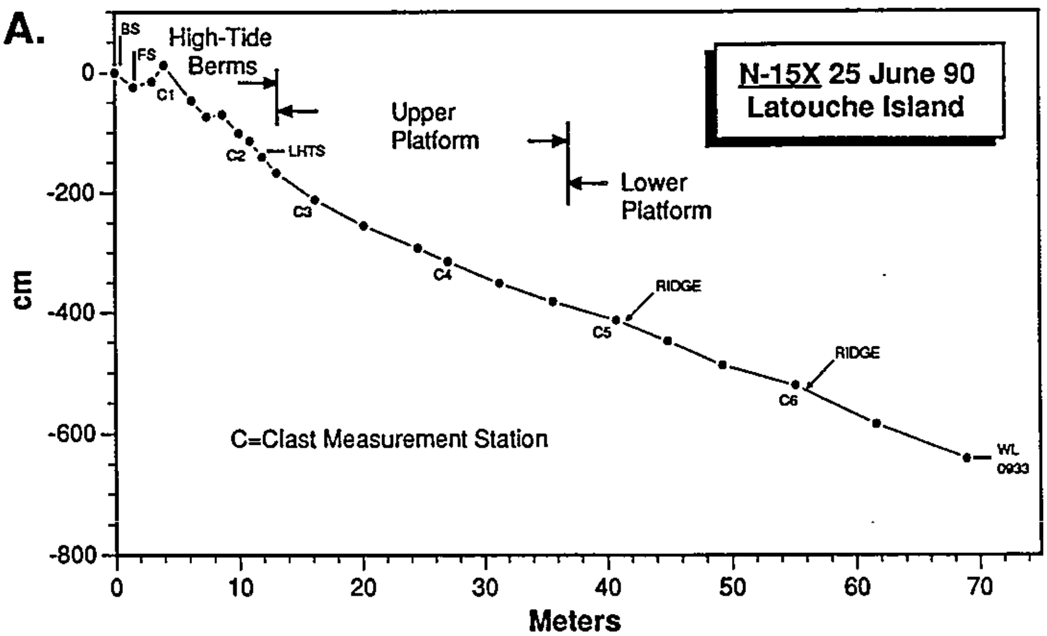


FIGURE 56. Map view sketch of the station N-15 pocket beach on the northeast end of Latouche Island, showing location of the permanent station N-15 and the two profiles run on 25 June 1990 (N-15X and N-15Y). Note the abundant berm-like ridges on the upper and middle platforms. Several lines of evidence suggest that primary sediment motion is from left to right (northwest to southeast). Station N-15 appears to be a focus of erosion on this pocket beach.



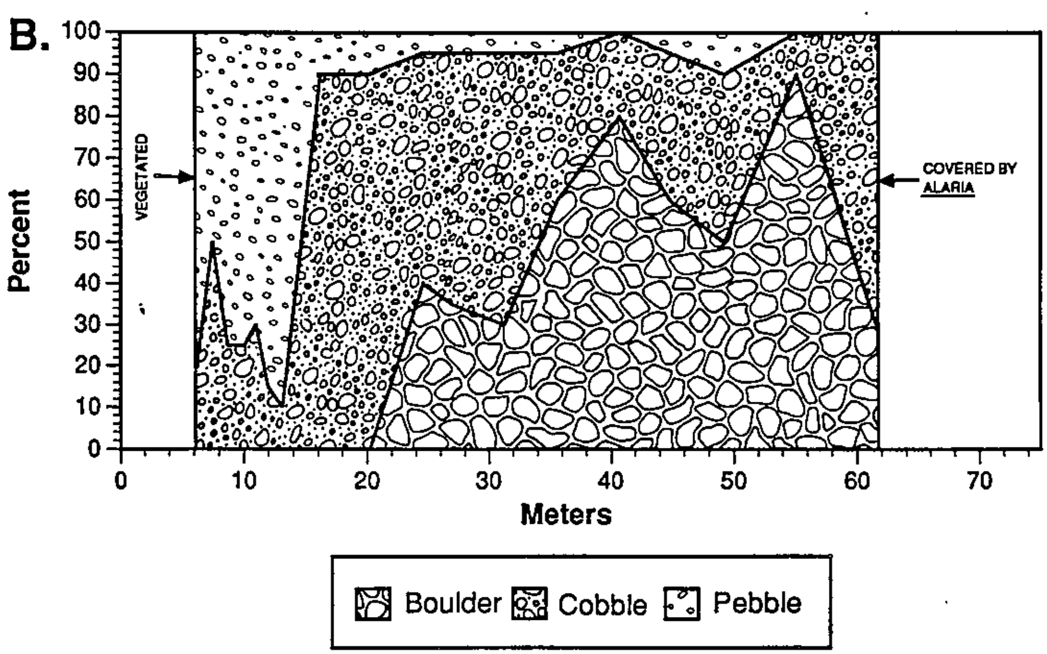


FIGURE 57. Station N-15X on 25 June 1990.

A. Topographic profile. Note presence of spring-tide berm and two subtle ridges on the lower platform.

B. Surface sediment distribution pattern along profile, which shows an abundance of pebbles on the high-level berms and dominance of boulders on the lower platform.

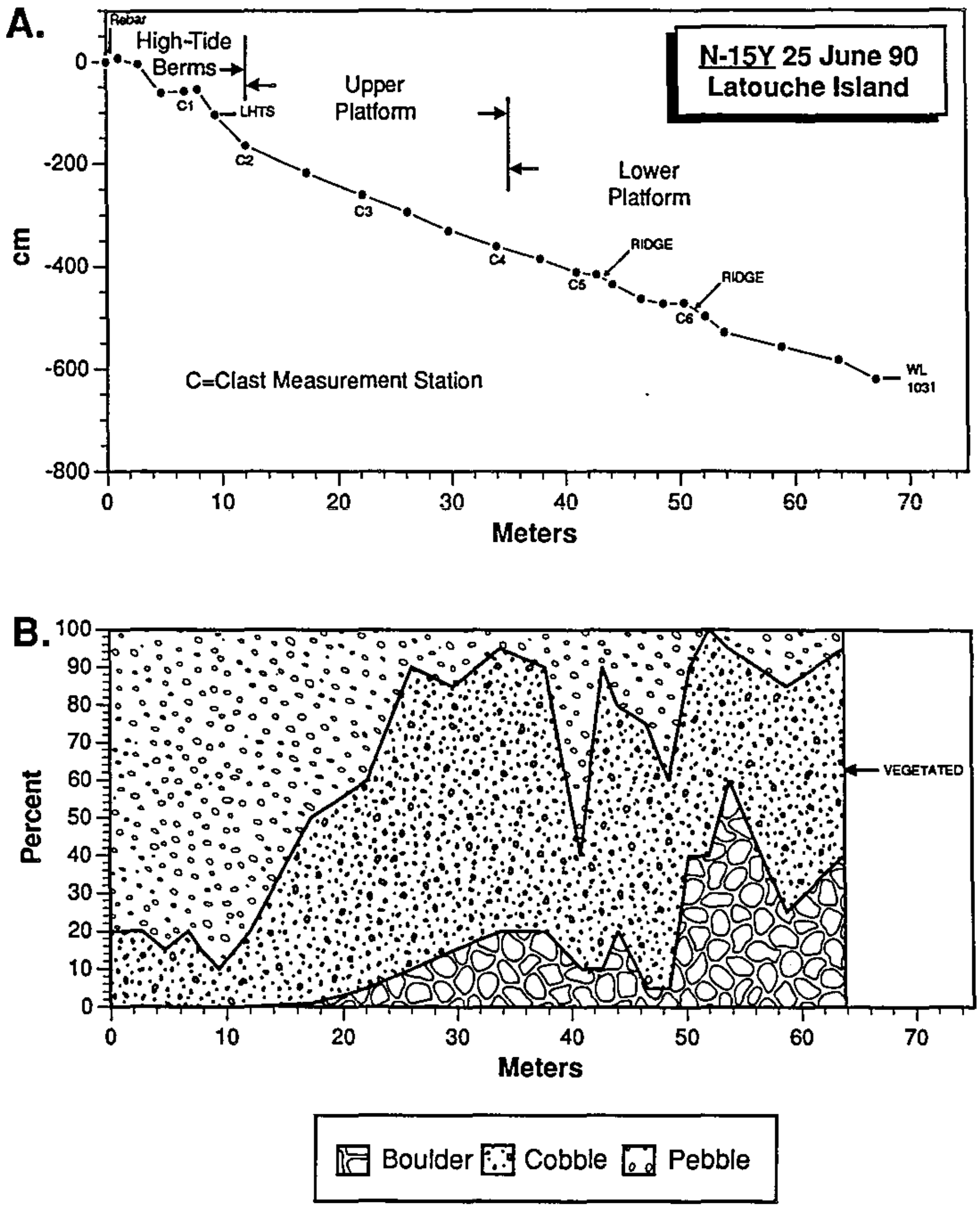


FIGURE 58. Station N-15Y on 25 June 1990.

A. Topographic profile. A well-developed spring-tide berm, made up mostly of pebbles, was present on this day. The storm berm crest is located one reading seaward of the rebar. Note presence of two berm-like ridges on the lower platform.

B. Surface sediment distribution pattern along profile. A simple fine-to-coarse pattern exists on the upper half of the profile, but the sediment pattern is complex over the berm-like ridges, being coarsest on the crests of the ridges and finest in the swales between them.

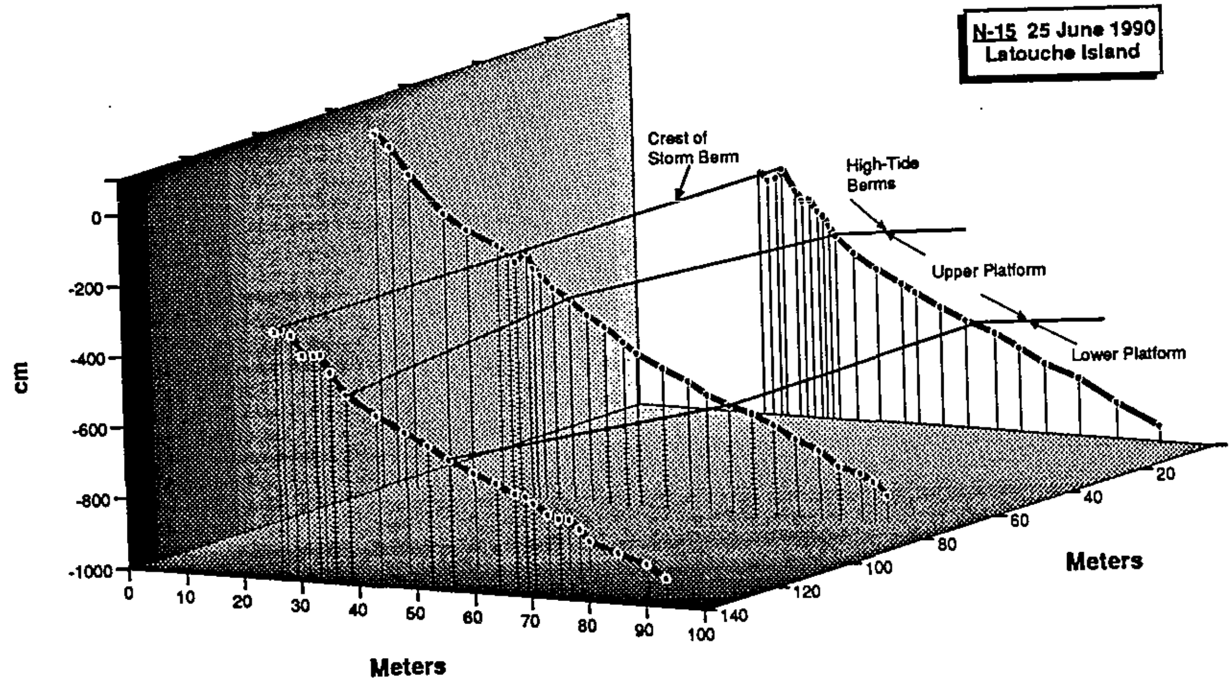


FIGURE 59. Three-dimensional plot of the three profiles measured at the station N-15 pocket beach. The intertidal zone consists predominantly of the upper and lower platforms, with relatively minor depositional features occurring at the high-tide line (spring and storm berms) and on the lower platform (berm-like ridges). Most of the surface of the platform is armored and the envelope of annual sediment motion is less than $\pm$ 30 cm.

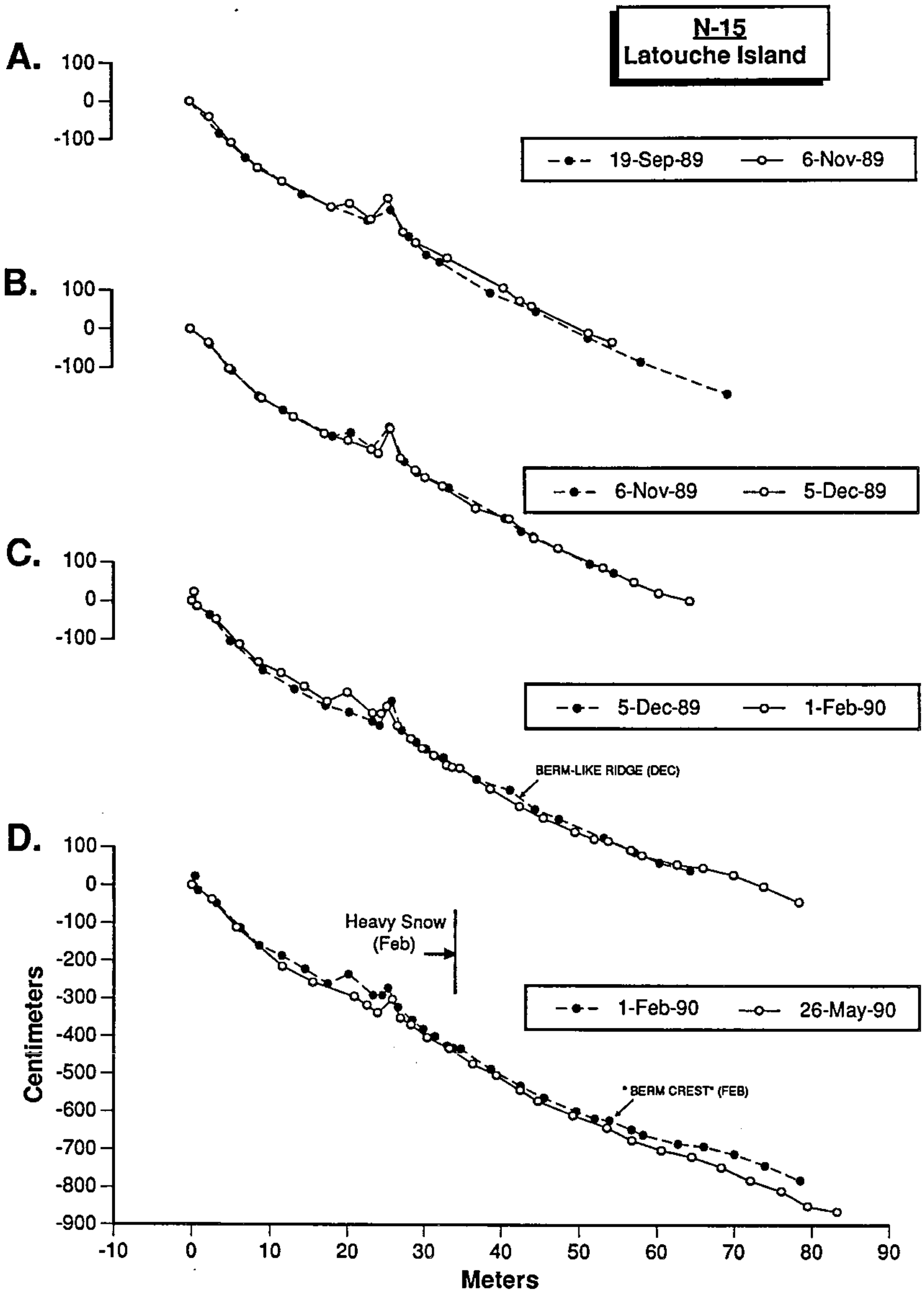
FIGURE 60. (Facing Page) Overlay plots of beach-profile surveys at station N-15.

A. (19 September 1989 and 6 November 1989) In this interval, the storm berm appears to have retreated slightly and to have been elevated a few cm. It was overtopped during the high spring tides of mid-October. There is no explanation in the notes for the elevation of the November profile offshore of the storm berm. This is possibly because the transects were slightly misaligned.

B. (6 November 1989 and 5 December 1989) The only change was the appearance of a berm-like ridge at the 37 m mark in December.

C. (5 December 1989 and 1 February 1990) Almost half of the profile was covered with snow in February. A new, larger berm-like ridge occurred on the lower part of the February profile.

D. (1 February 1990 and 26 May 1990) The only change was the southeasterly migration of the berm-like ridge off the profile, leaving only a subtle mound as a reminder of its former existence.



N-15
Latouche Island
A.
19-Sep-89
6-Nov-89
B.
6-Nov-89
5-Dec-89
C.
5-Dec-89
1-Feb-90
BERM-LIKE RIDGE (DEC)
D.
Heavy Snow
(Feb)
1-Feb-90
26-May-90
"BERM CREST" (FEB)
Centimeters
Meters

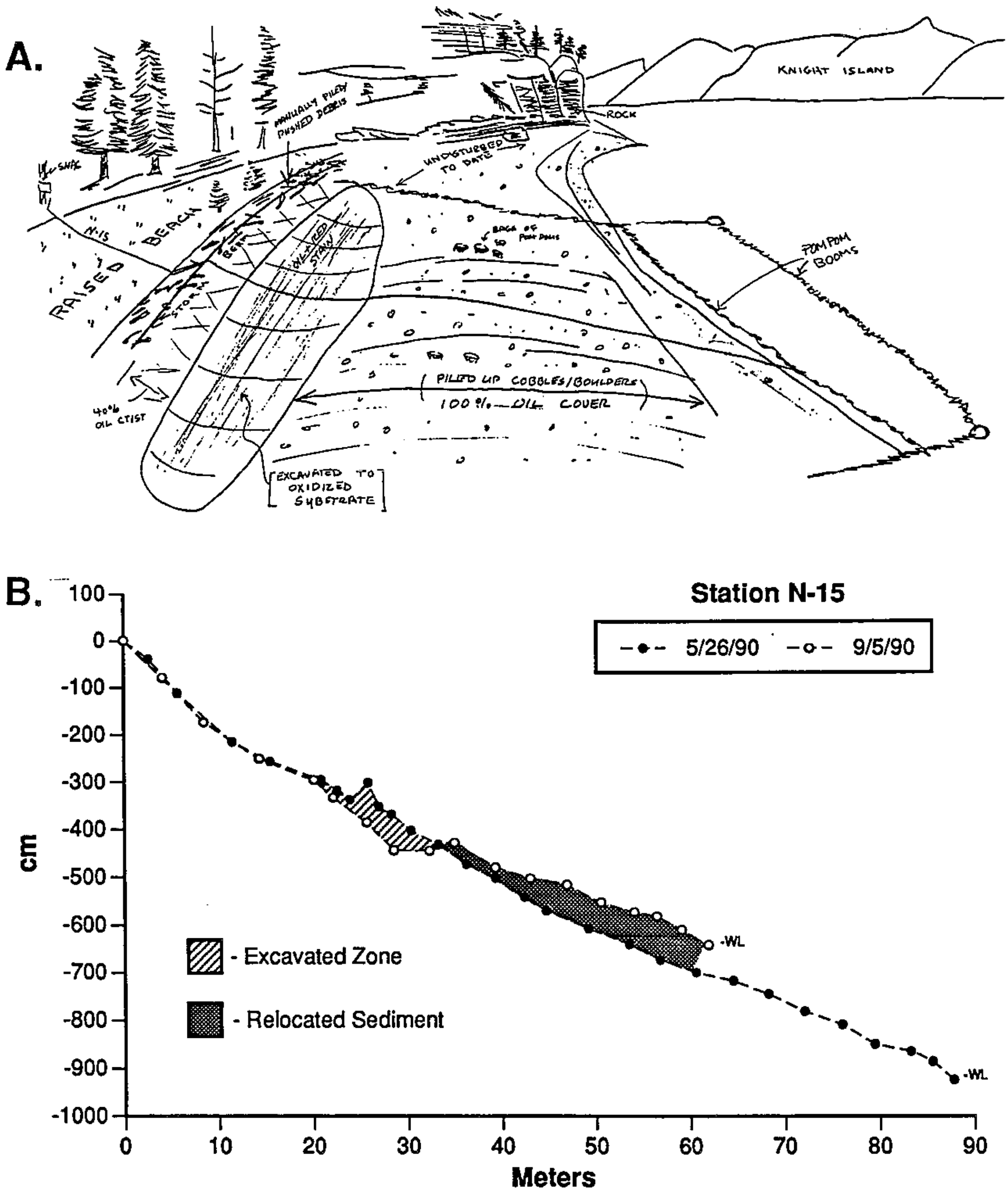


FIGURE 61. Berm relocation at station N-15.

A. Field sketch of station on 5 September 1990, showing large excavation pit and exposed oxidized surface.

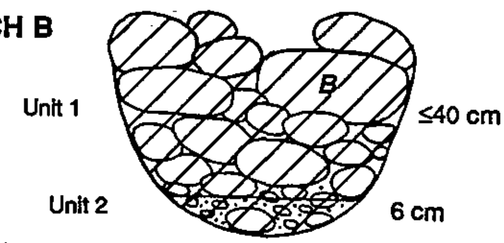
B. Comparison of 26 May 1990 and 5 September 1990 profiles, showing cross-section of sediment moved during process of berm relocation.

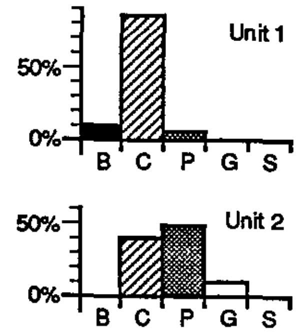
FIGURE 62. (Facing Page) Descriptions of trenches dug at station N-15 on 26 May 1990 (see Figure 52B for location of trenches), all of which were dug on the upper platform. Note excellent armoring and presence of oil at depth in all trenches.

N-15 NE LATOUCHE, 26 MAY 1990

- Oiled Zone

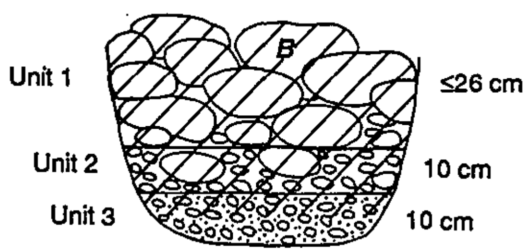
TRENCH B

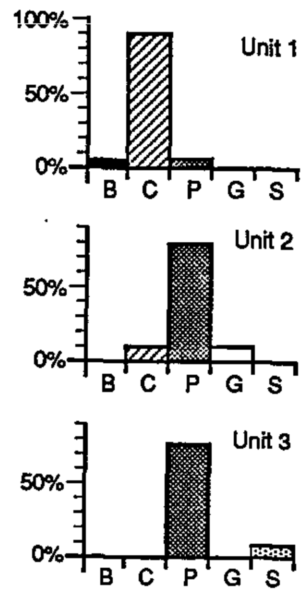




Unit 1: Top 20 cm, 30-50% stain
Lower 20 cm, mousse coating; coarsens upward
Unit 2: Mousse cover, dark brown; pooled at bottom

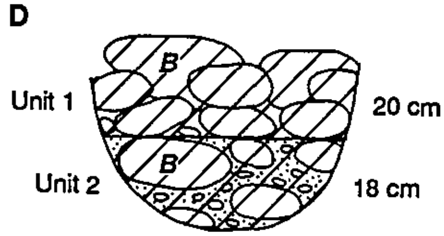
TRENCH C

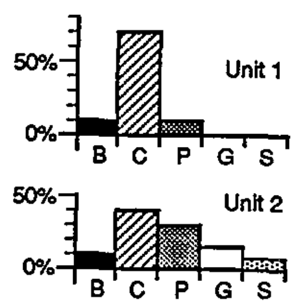




Unit 1: 5-10% residual stain; coarsens upward
Unit 2: Oil coating
Unit 3: Oil coating, upper 5 cm; red clay intermixed

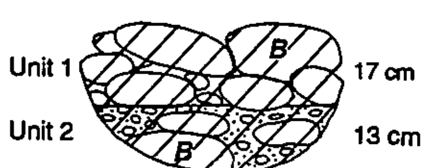
TRENCH D

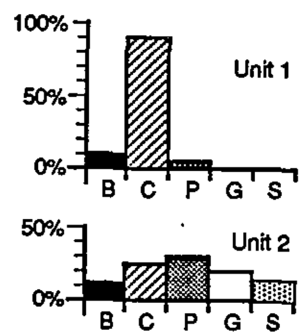




Unit 1: 5% scattered stain
Unit 2: Mousse coating, dark brown; pores not filled

TRENCH E





Unit 1: Sporadic splashes
Unit 2: Thin brown oil film

(NOTE: NO TRENCH DESCRIPTION FOR A)

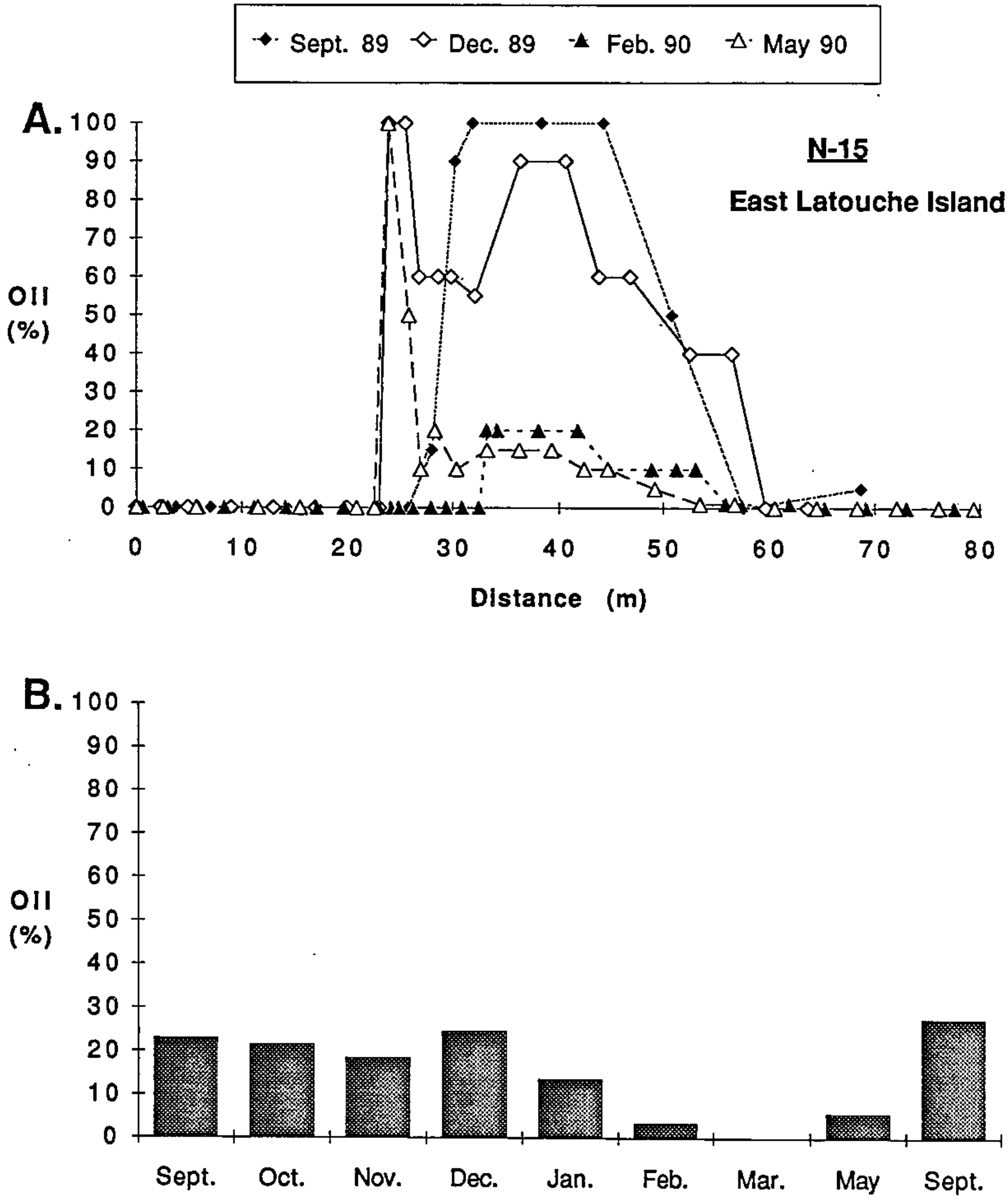


FIGURE 63. Plots of the percent coverage of surface oil along profile N-15 on Latouche Island.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 10. Sediment TPH (in ppm) results for N-15 on northeast Latouche Island.

Subsurface Samples

	High-Tide Berms		Upper Platform		Lower
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	Platform
9/89	32,440	42,040	1,500		60/3,590
10/89	6,160	10,100	10,110		
11/89		1,130	14,050		30
12/89	390		48,300		540
1/90		26,180		7,450	20
2/90		32,650		27,180	

Station N-17

Introduction. This station is located on a small east-facing pocket beach near Meares Point on Perry Island. The beach has typical high-tide berms and a well defined, slightly raised but steeply sloping shore platform in its lower reaches. Two levels of berm development were labeled "storm berms" on the field notes. The highly abraded sediments grade from fine to coarse in an offshore direction, and coarsen abruptly in both northerly and southerly directions away from the station, because of the proximity of bedrock. A small gravel tombolo is located just north of the profile. It is 22 km from this station to Naked Island in a due easterly direction. This fetch distance is affected somewhat by near-surface shoals at 3.5 km and the southern end of Lone Island at 9 km. An open effective fetch of 18 km is oriented in a southeasterly direction (45° to beach). Because of the easterly exposure, this beach is subject to considerable wave action and the erosional/depositional cycle on the beach could be clearly discerned. This beach is unique in that it is backed by a fresh-water lagoon, which generates a strong flow of groundwater through the coarse and well-sorted sediments. Groundwater flowed freely through trenches dug through-out the beach (Fig. 65B). This station was off limits in the spring and summer of 1990 because of a nearby active bald eagle nesting site. Perry Island was uplifted only 0.6 m during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the station on 7 September 1990 is given in Figure 64, and selected photographs of the site are presented in Figure 65.

N-17 7 Sept 90
Perry Island

A.

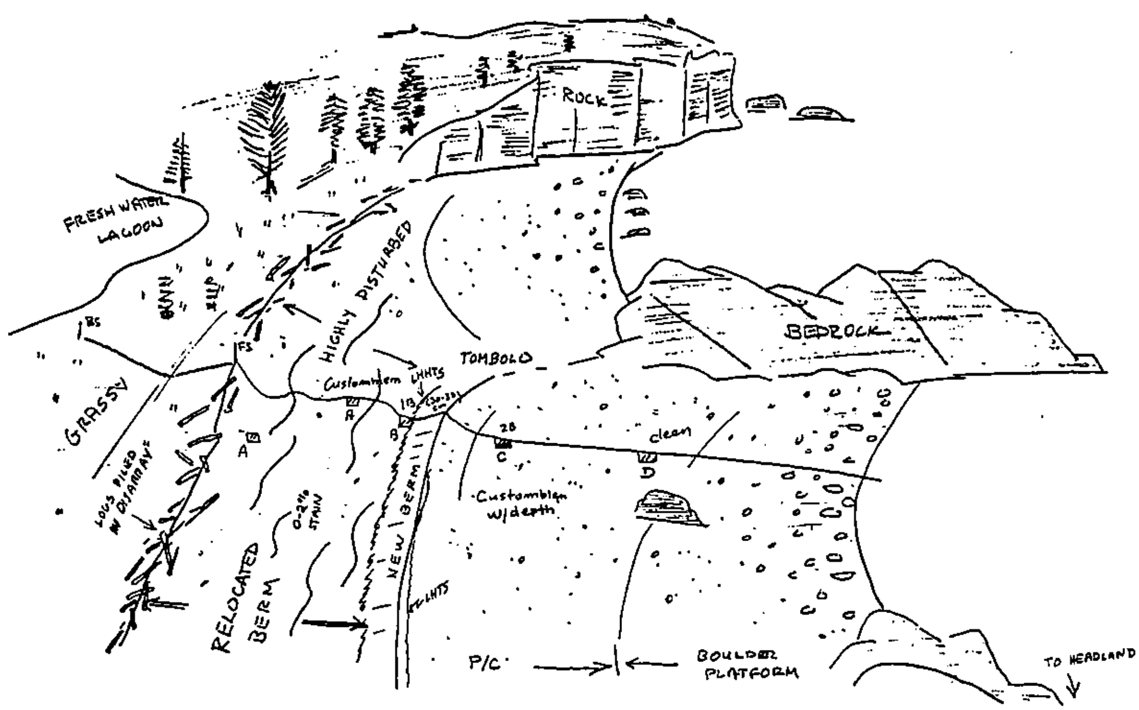
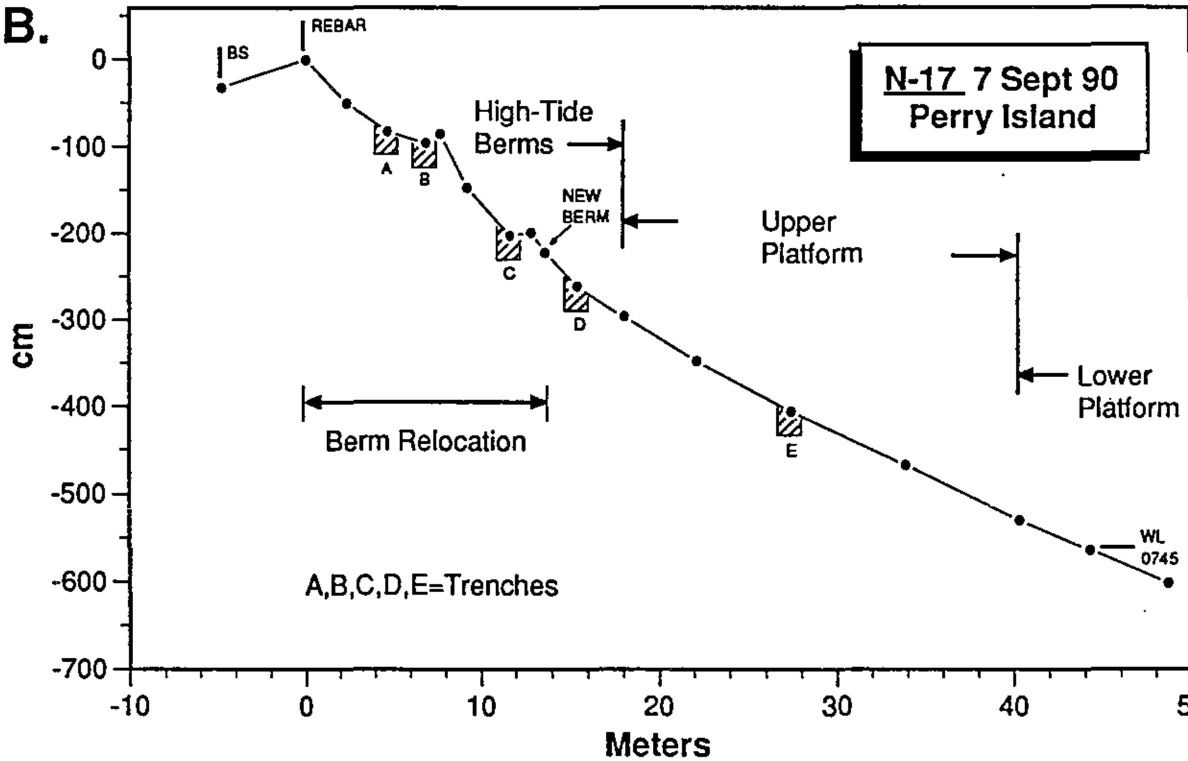


FIGURE 64. Station N-17 on the southern tip of Perry Island on 7 September 1990.

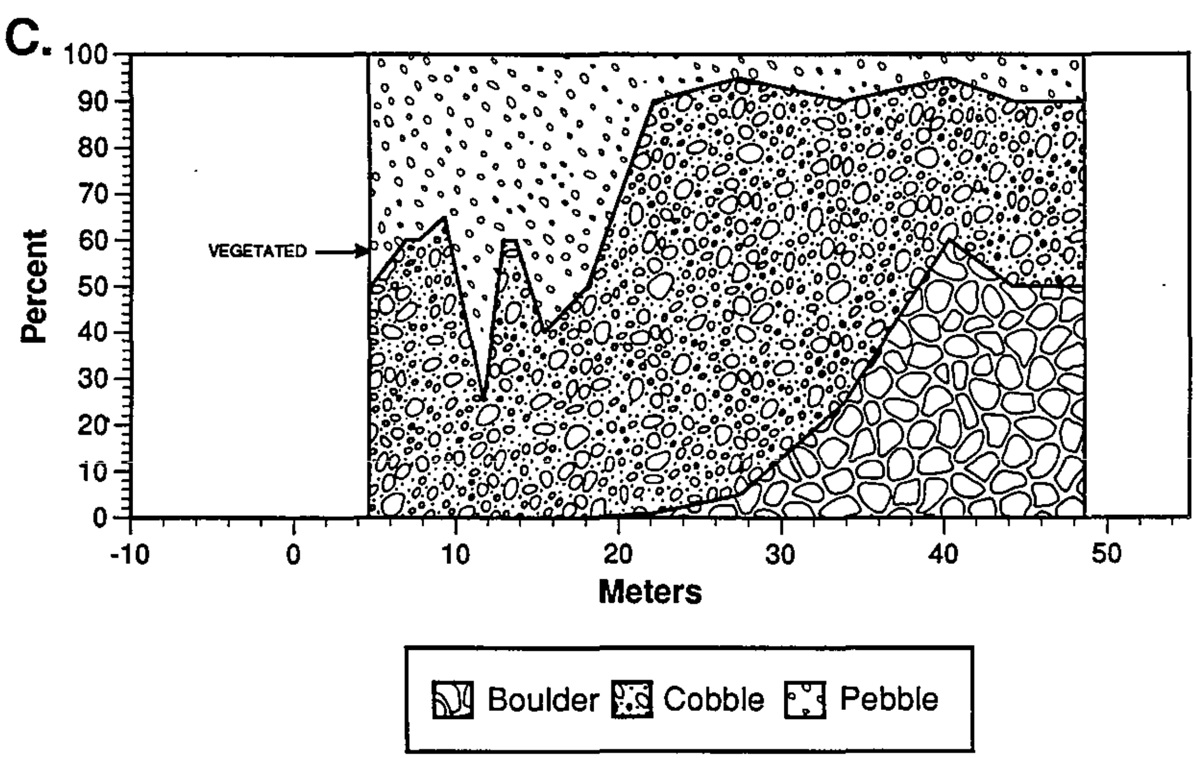
A. Field sketch. The upper part of the beach had been subjected to a major berm relocation in late August. A new berm had formed on the seaward side of the relocated sediment.

B. Topographic profile, plotted at a 5:1 vertical exaggeration. This is an exceptionally steep beach zone for this morphological class.

C. Surface sediment distribution pattern based on estimates of the 16 survey sites indicated by circles on B. This shows the same fine-to-coarse, offshore trend exhibited by the other stations in this class.



B.
BS
REBAR
High-Tide
Berms
NEW
BERM
Upper
Platform
Lower
Platform
Berm Relocation
A,B,C,D,E=Trenches
A
B
C
D
E
WL
0745
N-17 7 Sept 90
Perry Island
cm
Meters



C.
VEGETATED
Percent
Meters
Boulder
Cobble
Pebble

The station was heavily oiled by slicks which had milled around between Naked Island, Perry Island, and Eleanor Island for 3.5 weeks. Therefore, the oil was quite weathered and emulsified by the time it came ashore. The initial oil grounding was at mid tide; successive slicks covered the entire upper beach.

The shoreline was treated with warm-to-hot water washing and bioremediation in 1989. Manual removal of debris, berm relocation, and Inipol and Customblen addition were conducted in 1990.

Morphology and Beach Dynamics. Similar to the other stations in the cobble/boulder platforms with berms class, this beach is composed of three morphological units:

1) High-tide berms

   The zone between the front stake and ± 12 m on the profile always contained storm and/or spring-tide berms. These features, which were typically composed of near equal mixtures of pebbles and cobbles, were sometimes cuspate, an indication of the perpendicular approach and reflective character of the waves that molded the beach. The beachfaces of the berms dipped seaward at an average angle of 14°.

2) Upper platform

   This relatively featureless area is primarily a zone of sediment bypass. However, a berm-like ridge was present on 6 December 1989. The surface of the upper platform, which slopes seaward at 6°, is armored with cobbles.

FIGURE 65. (Facing Page) Photographs of station N-17.

A. Aerial view on 7 September 1990. Disrupted nature of berm area is result of recent berm relocation. Line shows position of the permanent profile. Note increase in grain size in off-shore direction. Photo by J. Michel.

B. Trench near middle of the upper platform on 6 December 1989. Note sheens on surface of groundwater table. The sediments of this beach were continuously flushed by groundwater. Photo by J. Michel.

A.

B.

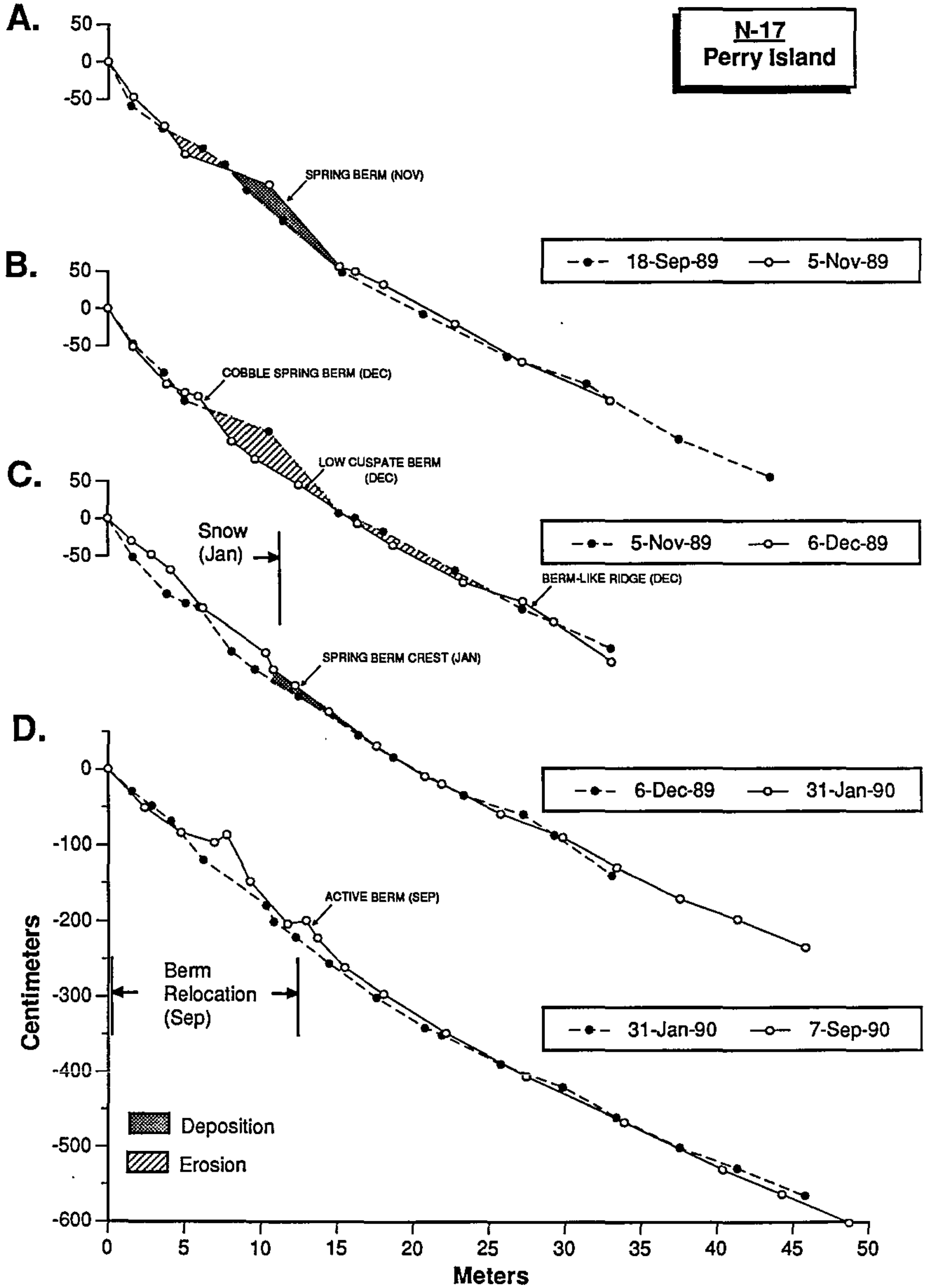
FIGURE 66. (Facing Page) Changes exhibited at station N-17 during the study period.

A. (18 September 1989 and 5 November 1989) Some erosion occurred on face of storm berm and a major new spring berm formed.

B. (5 November 1989 and 6 December 1989) The large spring berm was eroded away and a higher level, cuspate cobble berm replaced it. A lower level, flat cuspate berm and a berm-like ridge were also present.

C. (6 December 1989 and 31 January 1990) Snow covered the upper part of the profile. The berm-like ridge had been flattened and a minor spring berm was formed in front of the snow.

D. (31 January 1990 and 7 September 1990) The effect of the berm relocation activities are clearly shown.


N-17
Perry Island
A.
B.
C.
D.
SPRING BERM (NOV)
18-Sep-89
5-Nov-89
COBBLE SPRING BERM (DEC)
LOW CUSPATE BERM (DEC)
6-Dec-89
BERM-LIKE RIDGE (DEC)
Snow (Jan)
SPRING BERM CREST (JAN)
31-Jan-90
ACTIVE BERM (SEP)
Berm Relocation (Sep)
7-Sep-90
Deposition
Erosion
Centimeters
Meters

3) Lower platform

This is a slightly flatter (5°) extension of the upper platform surface. Boulders attain levels of 50-60 percent of the surface material. Bedrock crops out in several localities along the platform.

The beach profile at station N-17 was run only 5 times during the study. No major discrepancies in the data were found, probably because two survey stakes were present throughout the period. The series of overlay plots in Figure 65 show that this was a fairly dynamic station in the area of the high-tide berms. The lower reaches of the profile are solidly anchored in bedrock, so changes seen there involved only minor adjustments in the surficial armor.

Comparison of the survey plot of 18 September 1989 with that of 5 November 1989 (Fig. 66) shows that the storm berm was eroded slightly during the high spring tides of mid-October and a major spring berm was deposited in front of it by early November. By the time of the 6 December 1989 visit, most of the previous spring berm had been eroded away and a new, higher cuspate spring berm had formed. Michel commented in the field notes that the upper beachface "looked as if the oiled clasts had been eroded and mixed with clean ones". A low-level cuspate berm occurred at about the 12 m mark (Fig. 66). A clearly defined berm-like ridge composed of cobbles and boulders occurred near the middle of the upper platform (25-30 m). Because of the heavy snow cover during the 31 January 1990 visit, it is difficult to say what changes had taken place on the upper beach. An overlay of the 31 January 1990 and 7 September 1990 profiles is given in Figure 66, which clearly illustrates the disruption of the upper part of the profile by the berm relocation activities which took place in late August 1990. Waves had created a small, active berm on the seaward side of the relocated sediment by 7 September.

It is clear from a study of Figure 66 that the only significant sediment envelope that developed naturally on this beach occurred on the spring-tide berms. This amounted to a maximum vertical change of around 50 cm. The sediments on the beach are highly mobile, with maximum sediment transport being in an onshore and offshore direction, because of the limited lateral extent of the beach and the adjacent rocky headlands. Historically, there has been some northerly motion of sediments to create the tombolo behind the bedrock headland to the north, which is shown in the field sketch in Figure 64A and the photograph in Figure 65B. The biological assemblage on the sediments is further supporting evidence of the dynamic nature of this pocket beach. Although the September 1989 survey was conducted near low spring tide, no Fucus or other attached algae were noted; only abundant barnacles were present.

Sediments. The sediments of this beach are derived from the adjacent rock outcrops, which are composed of metamophosed shales, sandstones, and conglomerates of the Valdez group (Moffit, 1954). The surface sediment distribution along the profile on 7 September 1990 is shown in Figure 64C. The sediments of the high-tide berms, which had been highly mixed at that time by the berm relocation process, were half pebbles and half cobbles. A strong gradient of sediment size occurred across the upper and lower platforms, with pebbles decreasing abruptly down the platform to a value near 10 percent and boulders increasing to around 50 percent on the lower platform.

A total of 17 trenches were dug along the profile. All of the trenches dug in the berm relocation area during the 7 September 1990 survey contained vertically mixed sediments.

Oil Distribution Patterns. There were three zones of surface oil contamination during the survey in September 1989 (Fig. 67)—at the high-tide berms, on the upper platform, and a 6-m wide zone on the lower platform. This distribution reflects the nature of the initial grounding of the oil; this site was visited on 18 April 1989 when the oil first came ashore, and we observed the oil coat covering the lower intertidal zone. Later, slicks covered the mid and upper zones, thus the three bands of heavier oil on Figure 67. The oil occurred as a light-to-dark stain on the cobbles; the 1989 washing treatment had obviously removed the heavy oil coating. There were large accumulations of heavily oiled seaweed, both on the surface and with depth at this station. Bands of black oil covered the bedrock at both the northern and southern ends of the pocket beach.

By November, black stain remained on 50 percent of the cobbles of the spring berm, but the rest of the oil on the lower berms and platforms occurred as a thin film, which beaded when wet, or a sheen. By December, the oil films were nearly gone, though a large patch of irridescent sheen was present at the low high-tide line. Snow covered the upper zone on 31 January 1990, and only very light stain occurred elsewhere. When the site was next visited on 7 September 1990, the logs on the storm berm had been pushed back, and the storm berm itself relocated to the high-tide zone (Figs. 65A and 65D). The storm berm obviously had been removed down to clean sediments—the surface was highly disturbed, but only had about 2 percent coverage with an oily stain on the cobbles. More relocation work was done after the completion of our survey. The TPH results for surface sediments in Table 11 show very low levels in samples collected from September 1989 to February 1990.

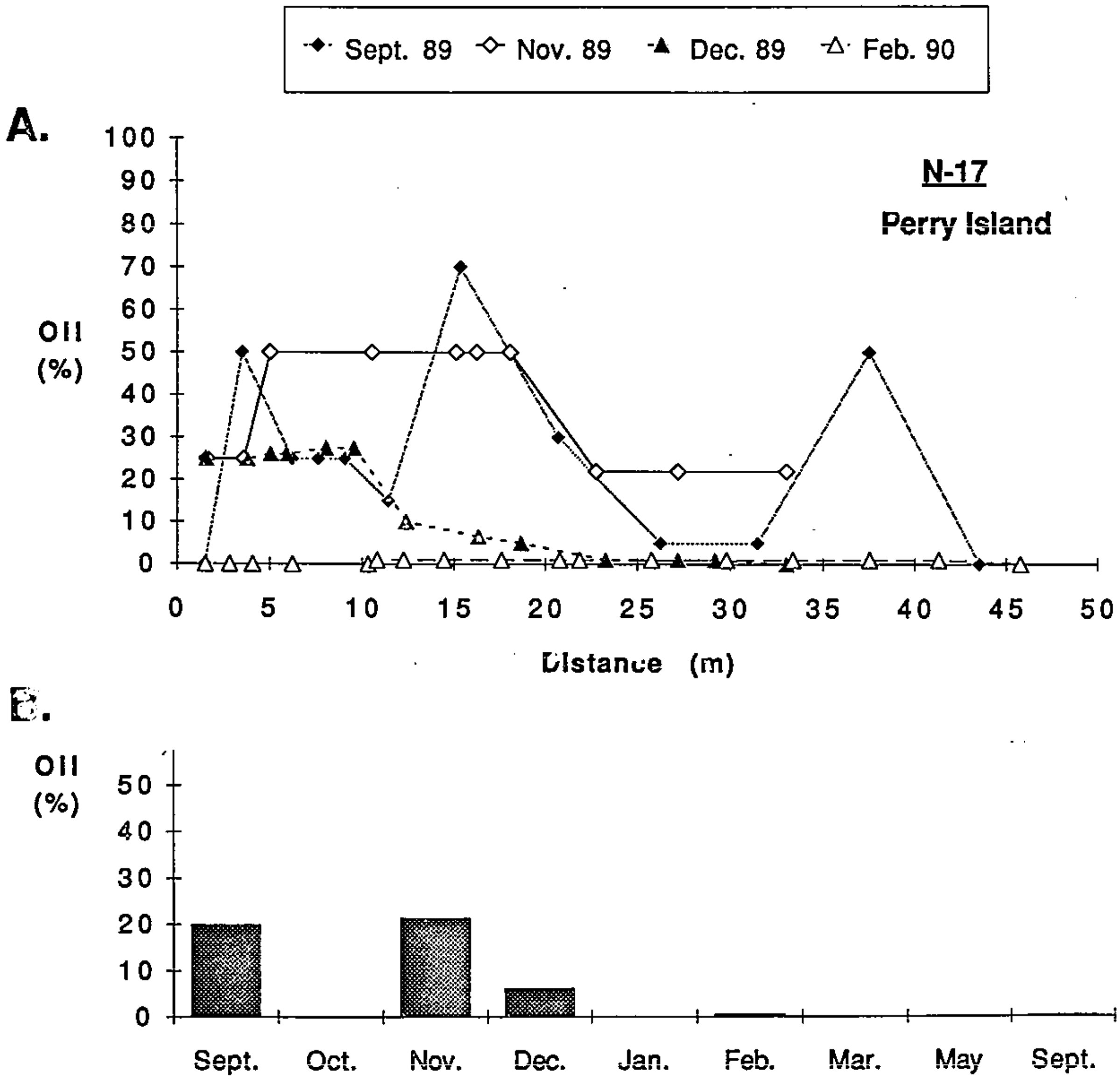


FIGURE 67. Plots of the percent coverage of surface oil along profile N-17.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

The oiling of subsurface sediments at this site was quite different than other sites, primarily, we think, because of the presence of so much groundwater discharge directly through the beach sediments. In every trench that reached the groundwater, water could be seen flowing through the substrate, and a sheen accumulated on the water surface. Oil on the sediments occurred as brown splotches or a film, rather than a black coating. TPH concentrations in samples from the upper platform through December 1989 (Table 11) show levels of 1,680-2,800 ppm, which seemed high for the visual appearance of the oil. But high accumulations of heavily oiled seaweed were found throughout the subsurface, particularly at the high-tide berms, and a small amount of oiled seaweed could significantly affect the results. The seaweed always looked fresh—much of the vegetation was still green—indicating that it was relatively recently deposited, which further supports the conclusion that the berms are active.

By 31 January 1990, TPH levels for samples were all very low, though they were all collected from less than 25 cm depths, due to sediment reworking and groundwater flushing. The oil leaking in the active beach had been dramatically reduced by nearly an order of magnitude. Like N-4 on Smith Island, this exposed beach with a shallow bedrock platform showed large oil removal over the storm season. Subsurface oil samples collected in September 1989 showed the highest degree of weathering of any subsurface samples from PWS. Almost all individual component peaks were gone and a large unresolved complex mixture (UCM) hump was all that remained. Thus, groundwater flow sped degradation of the oil as well as removal of it from the subsurface.

Relocation of the berm in late August 1990 changed the nature of the subsurface oil. The heavy, black oil in the storm-berm sediments was pushed over and mixed with the sediments of the high-tide berm. Samples from depths of 30-35 cm contained 5,550 and 7,820 ppm TPH (Table 11). The descriptions for trenches A, B, and C show oiled sediments at least 40 cm thick on top of the original surface, and Custombien granules were scattered throughout. It was also interesting to note that the water depth was deeper in September 1990 than usual, indicating that the piled-up sediments had not influenced the groundwater flow levels through the beach. Of all the NOAA stations where berm relocation was conducted, this site appears to have the greatest chance for success, because:

1) It has an active beachface, with regular erosion and deposition of the high-tide berms.

2) The berm was not pushed too far down the beach.

3) There was not a layer of heavily oiled sediments already below the original beach surface.

4) There was not a significant amount of sand-sized sediments in the berm that could have been eroded and deposited offshore.

5) There was not a particularly rich intertidal community at the site.

TABLE 11. Sediment TPH (in ppm) for N-17 on Perry Island by morphological zone.

Surface Samples

Date	High-Tide Berms	Upper Platform	Lower Platform
9/89	70/170		
11/89	<10	50	
12/89	30/370	90	
2/90	40	40	

Subsurface Samples

	High-Tide Berms		Upper Platform		
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	Lower Platform
9/89	2,520		2,800		520
11/89		<10	2,420		370
12/89	2,470	30/640	1,680		
2/90	30		130		30
9/90		7,820		5,550	

RAISED ROCKY PLATFORMS WITH MINIMAL SEDIMENT

General Description of Shoreline Type

The second morphological category of investigation during the NOAA monitoring study in PWS was one we refer to as raised rocky platforms with minimal sediment. The major difference between this class and cobble/boulder platforms with berms is primarily the absence of gravel material in quantities great enough to cover the surface of the raised platform or to be reworked into berms on its landward side. This type of area would be mapped with a ranking of 2 on the ESI index, because of the tendency for oil to be readily cleansed from the exposed bedrock surface. We found that 10.4 percent of the shoreline of PWS exposed to the EXXON VALDEZ spill was of this shoreline type. We had one permanent station, N-2, that represents this class. The permanent markers established during the 16 September 1989 survey were lost, and the profile was re-established in the near vicinity during the 20 October 1989 survey.

Station N-2

Introduction. This station, which is located on a raised platform that faces northwest, is positioned a little over 1.5 km from the northeast end of Green Island. The raised platform is composed of upturned (nearly vertical) beds of banded slate and shale, plus some relatively thick (a meter or so) beds of sandstone (Moffit, 1954). Because of the presence of an offshore island, the exposure of the shore in a perpendicular direction (NW) is small, less than 2 km. However, effective fetch to the north, or 45° to the shoreline, is 20 km, and, more importantly, the nearby northeast end of the island has an open, effective fetch of 55-60 km to the northeast. It is clear that any major northeasterly wind would generate large waves that would wash over this rock platform, which was raised around 2.4 m during the 1964 earthquake.

The oiling condition of the site is typical of the northeastern shoreline of Green Island, which had moderate to heavy oiling. The actual station site was moderately oiled; the oil came ashore as narrow bands of heavy accumulation, mostly at the high-tide line, and zones of splatter. Shoreline treatment consisted of warm-to-hot water washing and Inipol application in 1989. This section of shoreline was not as heavily washed as the western section of Green Island. As far as we know, only manual removal of oily debris was conducted in 1990.

RAISED ROCKY PLATFORMS WITH MINIMAL SEDIMENT

General Description of Shoreline Type

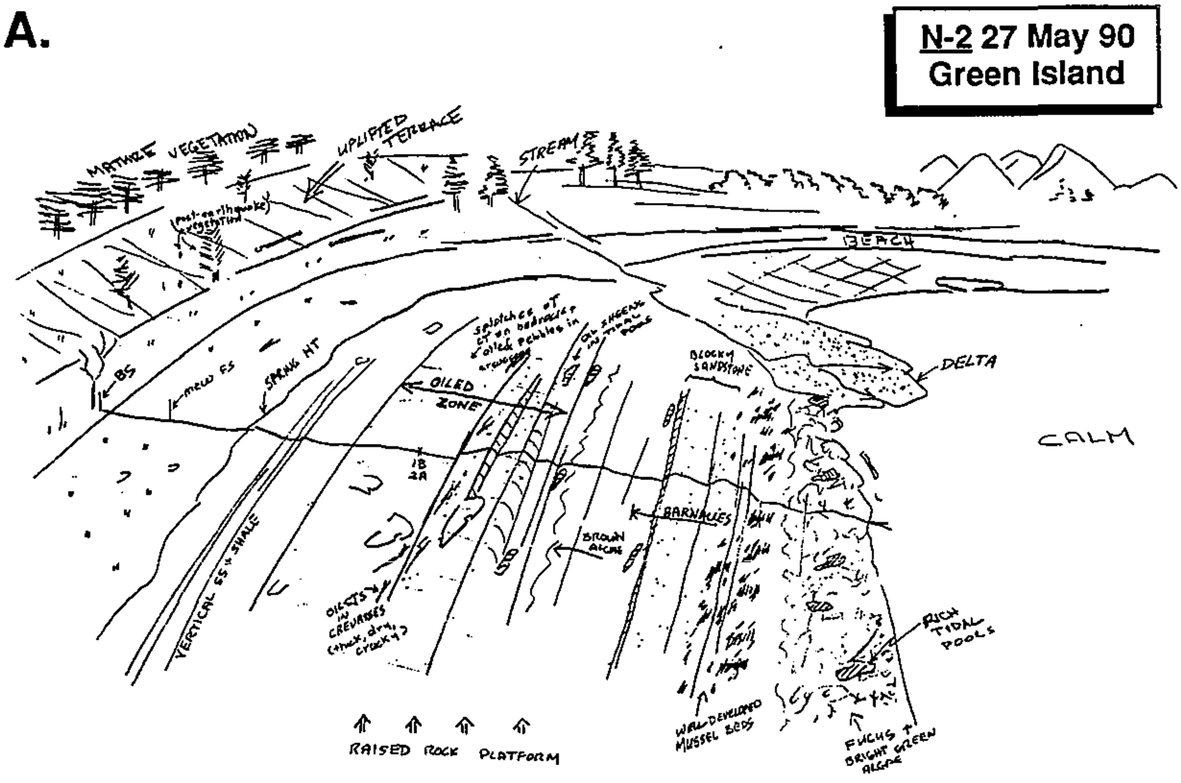
The second geomorphological category of investigation during the NOAA monitoring study in [illegible] was one we refer to as raised rocky platforms with minimal sediment. The major difference between this class and raised bedrock platforms with berms is primarily the absence of gravel material in quantities great enough to cover the surface of the raised platform or to be stranded into berms on its landward side. This type of area would be assigned with a ranking of [illegible] on the ESI index, because of the tendency for oil to be readily cleansed from the exposed bedrock surface. We found that [illegible] percent of the shoreline [illegible] exposed to the EXXON VALDEZ spill was of this shoreline type. We oversaw [illegible] that represents this class. The permanent stations established during the [illegible] September 1989 survey were [illegible], and the profile was re-established in the same vicinity during the [illegible] October 1989 survey.

Station [illegible]

[illegible]

The [illegible] conditions of the site [illegible] of [illegible] Island, which [illegible]. The [illegible] station [illegible] of the [illegible] [illegible]

A.



B.

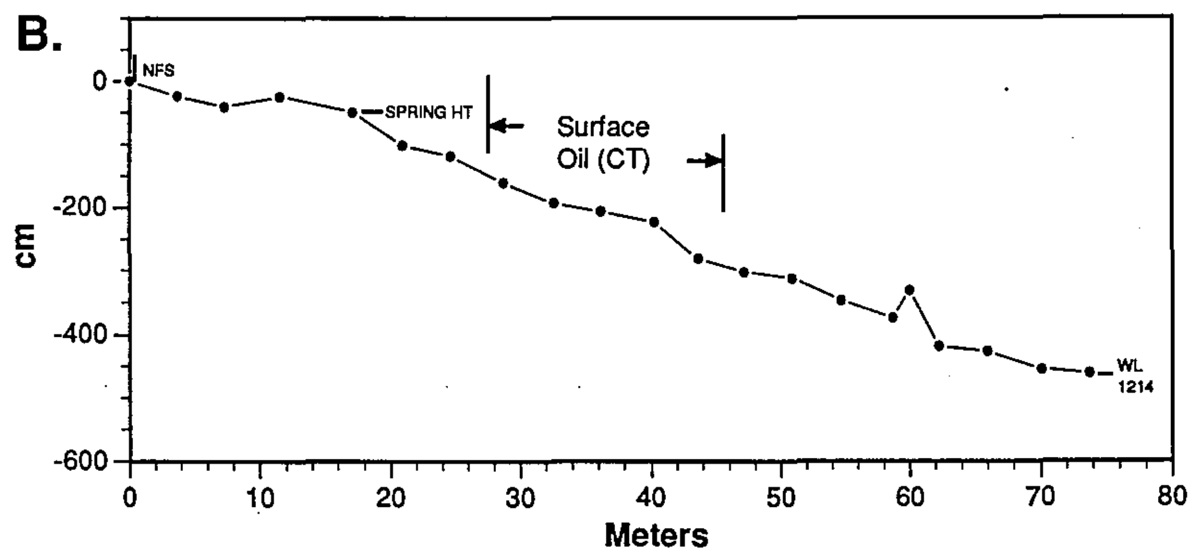


FIGURE 68. Station N-2 on 27 May 1990.

A. Field sketch. The irregular bedrock surface is caused by differences in composition among the vertically dipping sedimentary rocks. A scattering of oil splatter was present on the upper half of the intertidal zone. Attached epifauna and flora were abundant on the lower one-third of the raised rock platform.

B. Topographic profile. This is a general plot of the surface. No effort was made to show the surface topography of the individual beds in detail.

Morphology. The general morphology of station N-2 is illustrated by the field sketch and beach profile in Figure 68 and photographs in Figure 69. The station is a simple, raised rock platform without any beach development on the landward side. There are a few scattered pockets of boulders, cobbles, and pebbles, but nowhere do they cover the entire surface of the bedrock. The vertically dipping bedrock is mostly thin-bedded slates and shales, with two zones of thicker, blocky sandstone (Fig. 68). The profile measured on 25 May 1990 (Fig. 68) highlights some of the irregularities of the bedrock surface and shows a uniform offshore slope of 4°. There has not been enough time since the 1964 uplift for waves to plane the platform flat. Rich tidal pools dot the surface of the lower reaches of the platform, which is covered by abundant Fucus and other algae.

Oil Distribution Patterns. There was no change in the oil distribution at N-2 from October 1989 through February 1990. Figure 70 shows that the oil occurred as a 10 m wide band of 40-75 percent coverage near the high-tide line. The oil coverage was heavy, with thick patches of asphalt-type oil which appeared melted into the bedrock crevices and irregularities. The oil covered the sides of large bedrock benches as well. The middle part of the platform had scattered splotches of oil. Thin sheens in the tidal pools were reported in November 1989, and January, May, and September 1990.

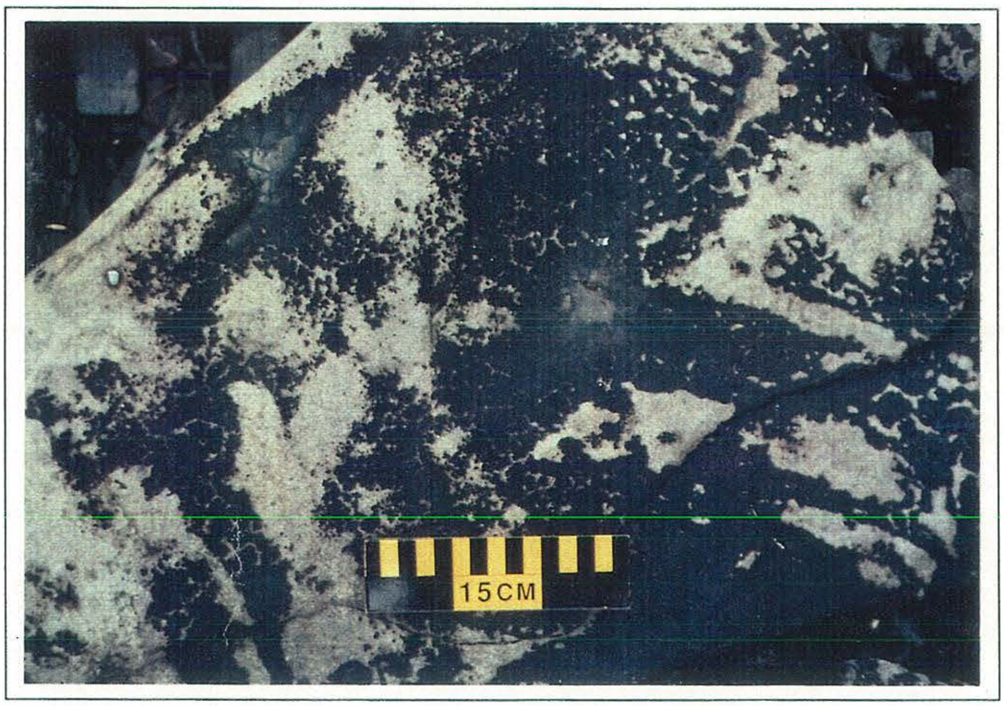
FIGURE 69. (Facing Page) Photos taken at station N-2.

A. View to south from near 30 m mark on 6 November 1990. This part of the platform had up to 30 percent surface oil coverage on this date. Photo by L. Sharman.

B. Flaking oil in splatter zone of the upper part of the platform on 27 May 1990. Photo by J. Michel.

A.

B.



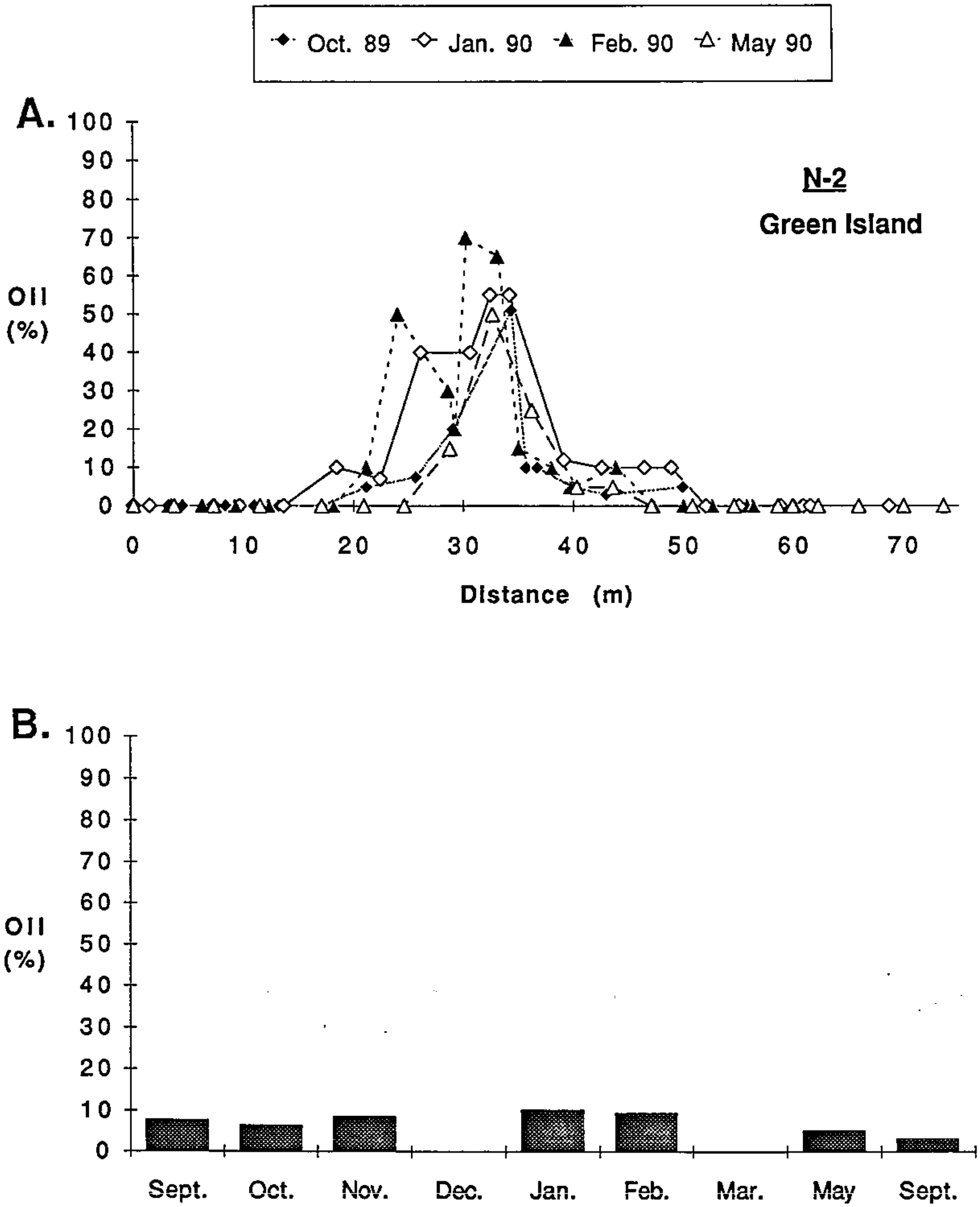


FIGURE 70. Plot of surface oil coverage at selected periods at N-2.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

During the May and September 1990 surveys, the heavy oil band was described as 40-50 percent coverage, with splashes of oil on the vertical sides of boulders and bedrock (Fig. 69B). The oil was still thick and soft, even liquid in some crevices. The only likely natural removal processes would be dessication or abrasion during a very large storm.

Observations on Biota. The middle of the platform had very large numbers of litterine snails in many of the tidal pools, even those which also contained heavy oil. The lower intertidal zone was extremely rich with heavy growths of green, red, and brown algae, eelgrass, seastars, anenomes, hermit crabs, and other organisms.

BAYHEAD BEACHES

General Description of Shoreline Type

This shoreline type occurs at the head of small bays which have a modest supply of sediments provided by small streams. Some of the beach sediment was eroded from adjacent bedrock outcrops. Most streams in PWS build small deltas in the intertidal zone, and all of any significant size are host to anadromous fish during the spawning season, with pink salmon usually being the most common type.

Two of the permanent NOAA stations, N-18 and N-14, which occur at the heads of Sleepy Bay and the West Arm of Northwest Bay, respectively, fit into this category. Both of these stations contained mobile pebble berms and low-tide bars during the study period, which indicates a moderate level of wave action. Because of their proximity to the anadromous streams, both stations received special attention during the cleanup period.

Station N-18

Introduction. This station is located at the south end of Sleepy Bay, a north-south oriented indention of the north end of Latouche Island (Figs. 16 and 71). Two additional stations, N-18X and N-18Y, were surveyed on 26 May 1990. A detailed location map of the expanded study area is given in Figure 72. The study area is bisected by a small anadromous stream that is constantly shifting positions as it builds a small delta. This area was uplifted about 3.7 m during the 1964 earthquake.

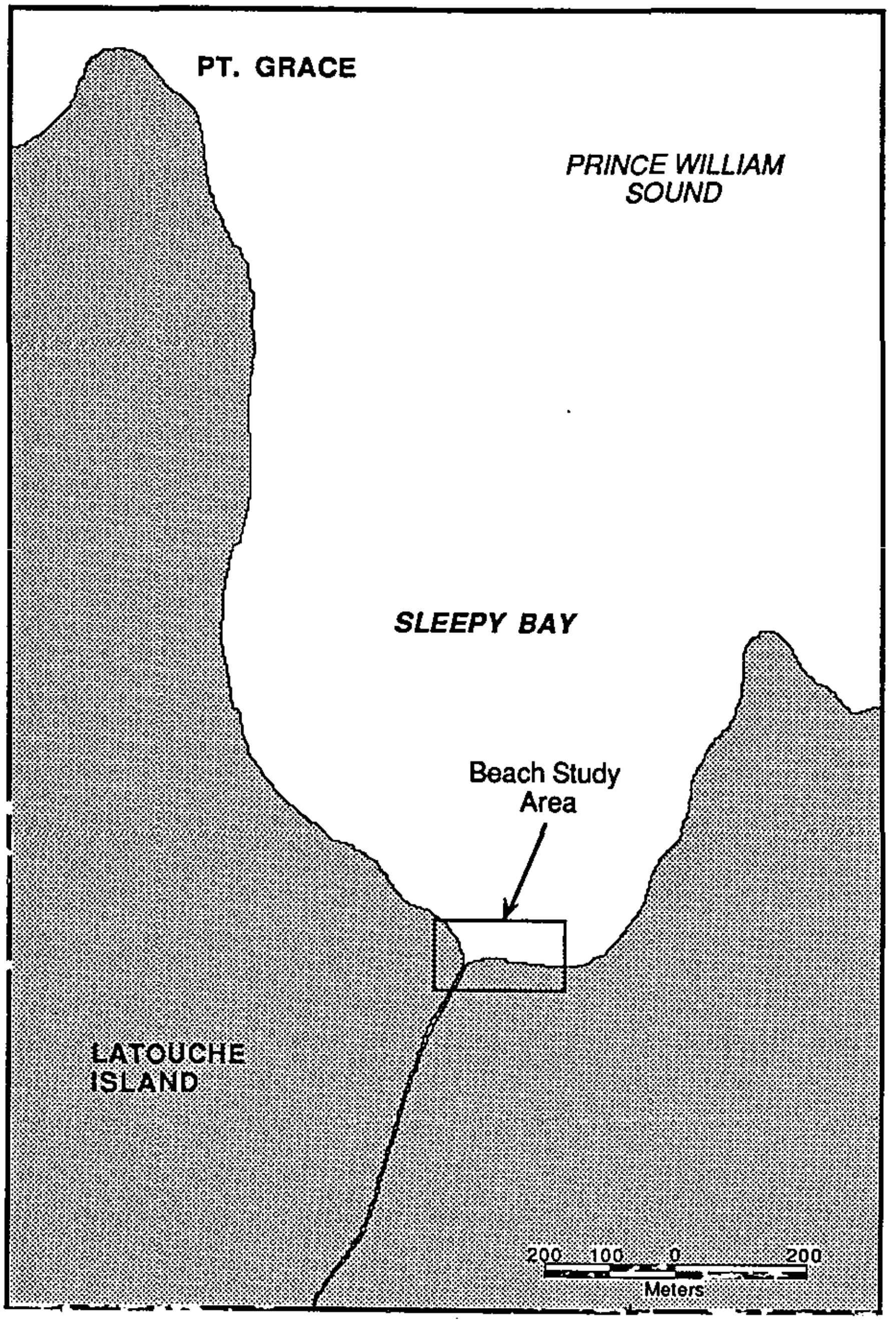


FIGURE 71. Map of Sleepy Bay showing the location of the area studied.

Being located at the very head of Sleepy Bay, this beach is somewhat sheltered. Even so, judging by the way the beach has changed over the past year, significant wave action does occur from time to time. The effective fetch to the north along the long axis of the Bay is about 10 km. Open effective fetch distances stretch 15 km in a northwesterly direction and 25 km in a northeasterly direction away from the entrance to the Bay. No doubt waves generated by winds blowing down these longer fetches reach the head of the Bay at times.

A field sketch, beach profile, and sediment distribution plot for station N-18 are given in Figure 73 and photos of the site are shown in Figure 74. Topographic profiles and surface sediment distribution plots for profiles N-18X and N-18Y are given in Figures 75 and 76.

A large oil slick entered Sleepy Bay in late March 1989 and heavily contaminated the shoreline. Along the porous gravel stream banks at the bay head, oil had penetrated to depths greater than 120 cm, the deepest observed at any location. Heavy oil accumulations covered the entire Bay, including the rocky platforms at both headlands.

Shoreline cleanup in Sleepy Bay posed numerous problems during 1989 and 1990, mainly because of the very heavy oiling and the anadromous fish stream. Crews used extensive hot-water washing with maxibarges throughout much of the Bay in June and early July 1989, until the onset of salmon spawning in the stream shutdown operations about 10 July. In an effort to clean up the stream bank prior to spawning, the use of mechanical equipment to excavate the oiled sediments along the stream banks was permitted. The idea was to remove the oiled sediments and replace it with clean sediment from the small delta platform just east of the stream. It was during this excavation work that the deep penetration of oil was discovered, not with hand-dug trenches. Eventually, clean sediments were placed adjacent to the stream with the use of some retaining material. However, the shoreline just east of the stream was only partially treated before excavation began. Also, the excavated oiled sediments from the stream bank were spread across this area. In mid-September 1989, bioremediation crews applied Inipol and Customblen to all the shoreline of Sleepy Bay, exclusive of a section 50 m on either side of the anadromous stream.

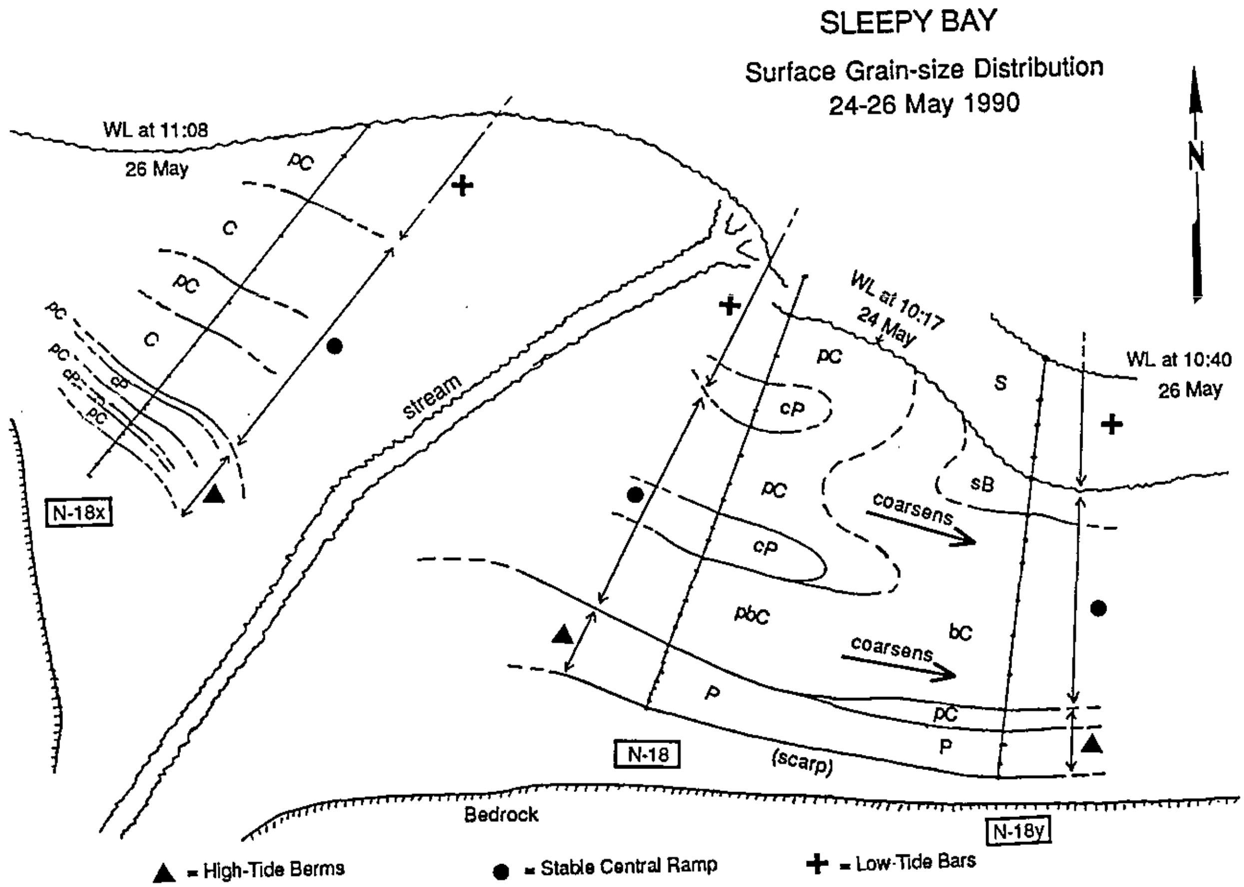


FIGURE 72. Detailed map of study area at the head of Sleepy Bay. Note location of the three profiles studied. Station N-18 is the permanent NOAA monitoring site. A general surface sediment distribution map is also shown. The larger letters signify the dominant sediment type (e.g., sB = sandy boulders, with boulders making up more than 50 percent of the total).

N-18 24 May 90
Sleepy Bay;
Latouche Island

A.

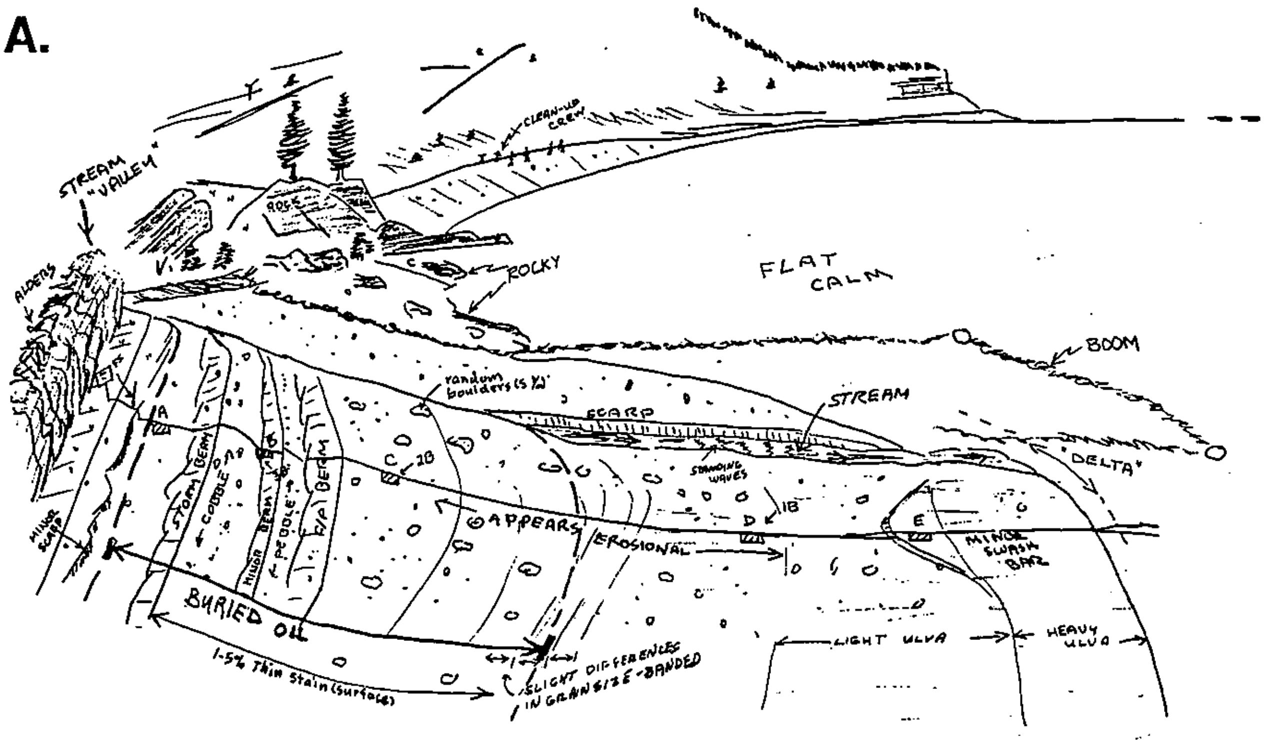


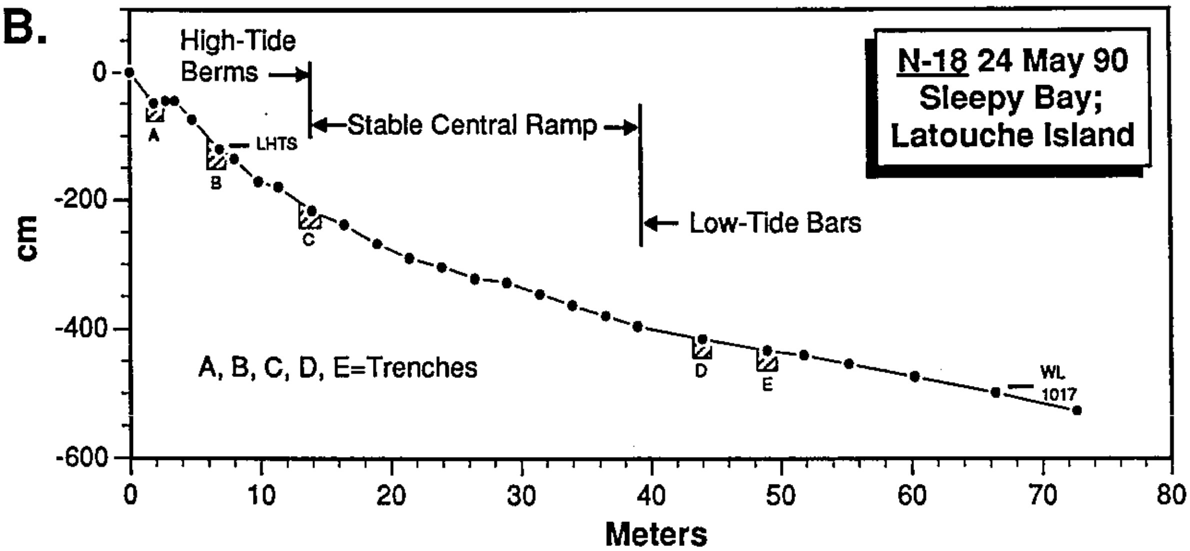
FIGURE 73. Station N-18 on 24 May 1990.

A. Field sketch. At the time of this survey, buried oil was restricted to the upper half of the profile. Note multiple berms near the high-tide line and minor swash bar near low water.

B. Topographic profile showing location of the three primary morphological components of the profile, as well as location of trenches dug on this day.

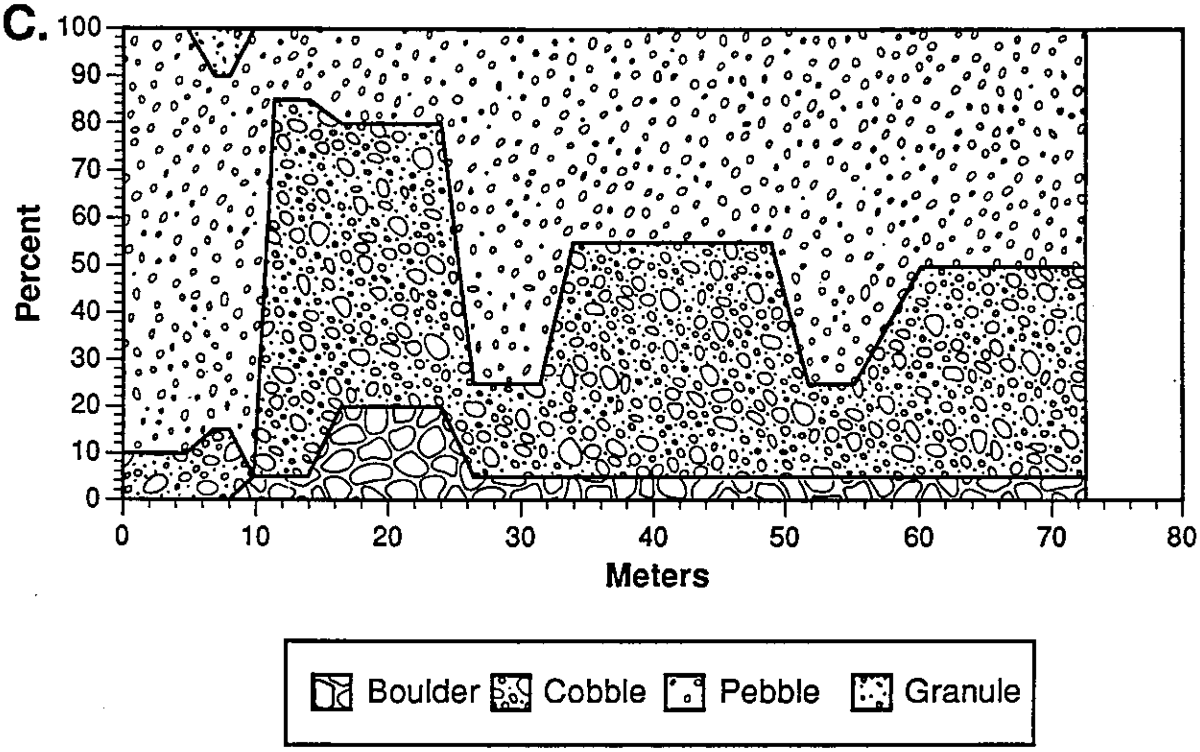
C. Distribution of surface sediments along the profile as determined by grain-size estimates at each of the survey points (circles on B). Note dominance of pebbles on the high-tide berms and peculiar banding of gravel types across the rest of the profile. The origin of the surface banding is unknown.

B.



High-Tide Berms
Stable Central Ramp
Low-Tide Bars
N-18 24 May 90
Sleepy Bay;
Latouche Island
LHTS
A
B
C
D
E
A, B, C, D, E=Trenches
WL
1017
cm
0
-200
-400
-600
0
10
20
30
40
50
60
70
80
Meters

C.



Percent
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
Meters
Boulder
Cobble
Pebble
Granule

In 1990, the extent of remaining oil still posed cleanup dilemmas. The oiled sediments at the head of the Bay were considered for rockwashing, but that treatment was considered too intrusive. Instead, extensive berm relocation was approved and carried out. Spot washing and manual removal was conducted along the rocky platforms. Nutrient applications were made in association with berm relocation.

Morphology and Beach Dynamics. The three profiles at this site have been subdivided into three morphological units:

1) High-tide berms

   The upper ± 10 m of the profile typically consists of a number of spring- and neap-tide berms, composed mostly of pebbles and cobbles. The berms at the top of profile N-18 (Fig. 73) were formed after that part of the beach was flattened during the high spring tides of mid-October. The average beachface slope for the three profiles was 12°.

2) Stable central ramp

   The central portion of profile N-18 showed little change over the monitoring period, except for a general lowering of the lower part of the zone by about 30 cm between the 5 December 1989 and 4 January 1990 surveys. This zone, which contains widely strewn boulders and slopes offshore on average of 4.5° (for the 3 profiles), appears to be a continuation of the slope of the adjacent land area.

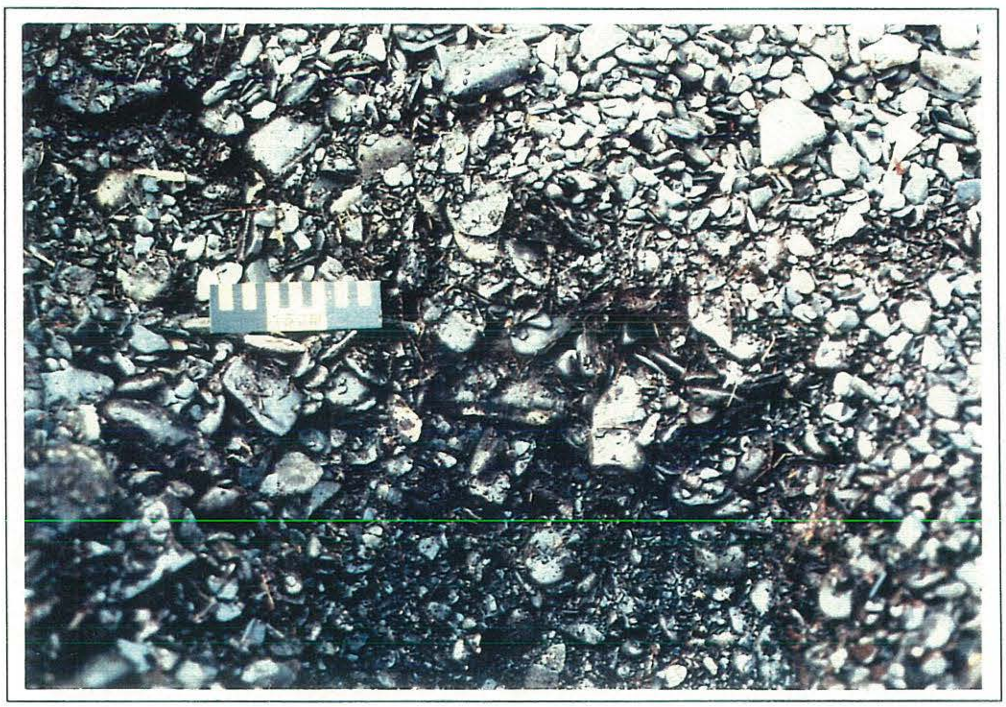
FIGURE 74. (Facing Page) Photos of the beach at the head of Sleepy Bay.

A. Oblique aerial view on 26 May 1990. The line shows location of NOAA's permanent station N-18. Photo by M. Hayes.

B. Trench A on profile N-18 on 24 May 1990 (see Fig. 73B for location). The upper 5 cm were clean, but oiling, which was heavy in places, extended to depths of 45 cm. Photo by J. Michel.

A.

B.



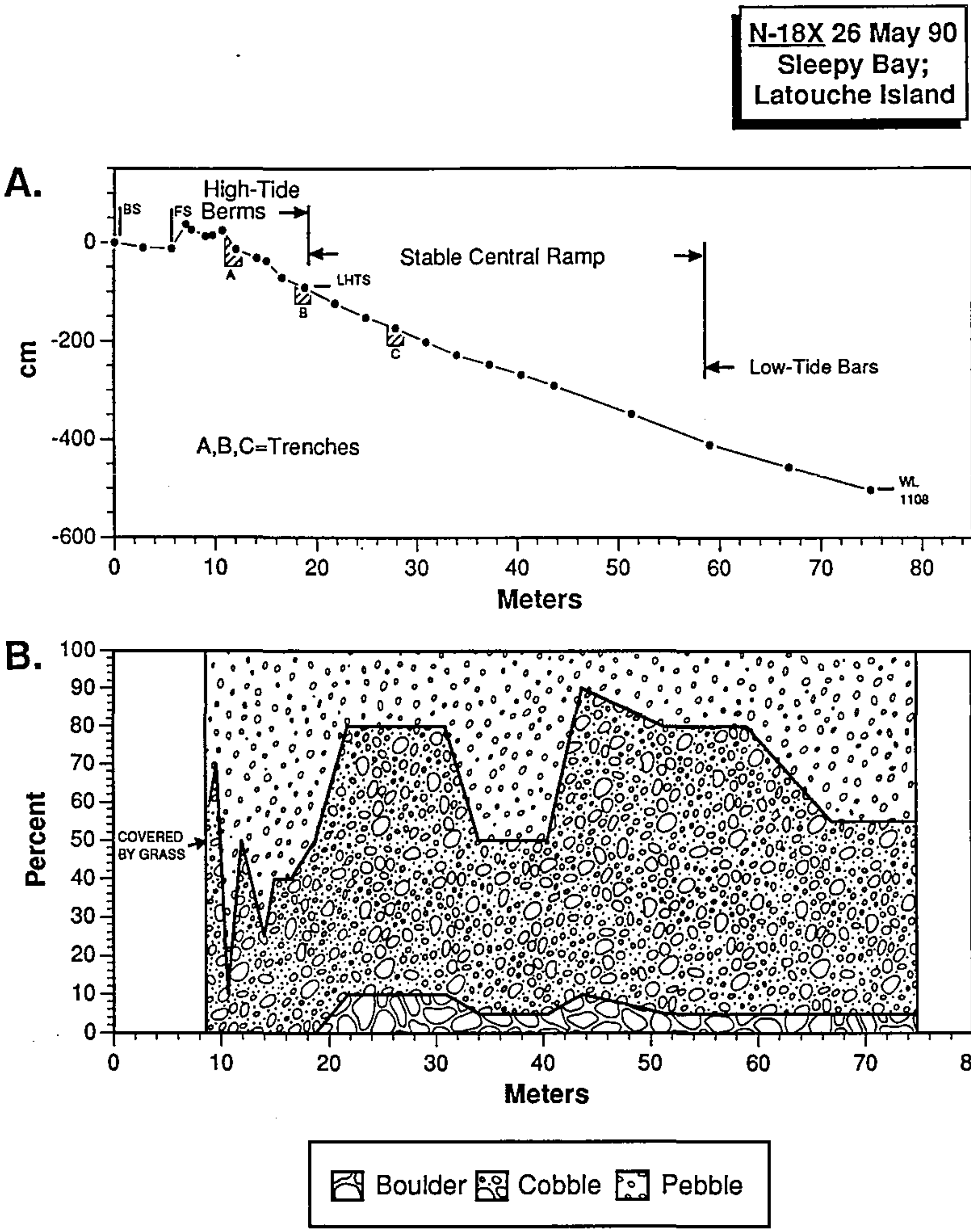


FIGURE 75. Station N-18X on 26 May 1990.

A. Topographic profile. Note well-developed berms near high tide and the relative smoothness of the rest of the profile.

B. Surface sediment distribution based on estimates at each of the survey points (circles on A). Note dominance of pebbles at the high-tide area and cobbles over the rest of the profile.

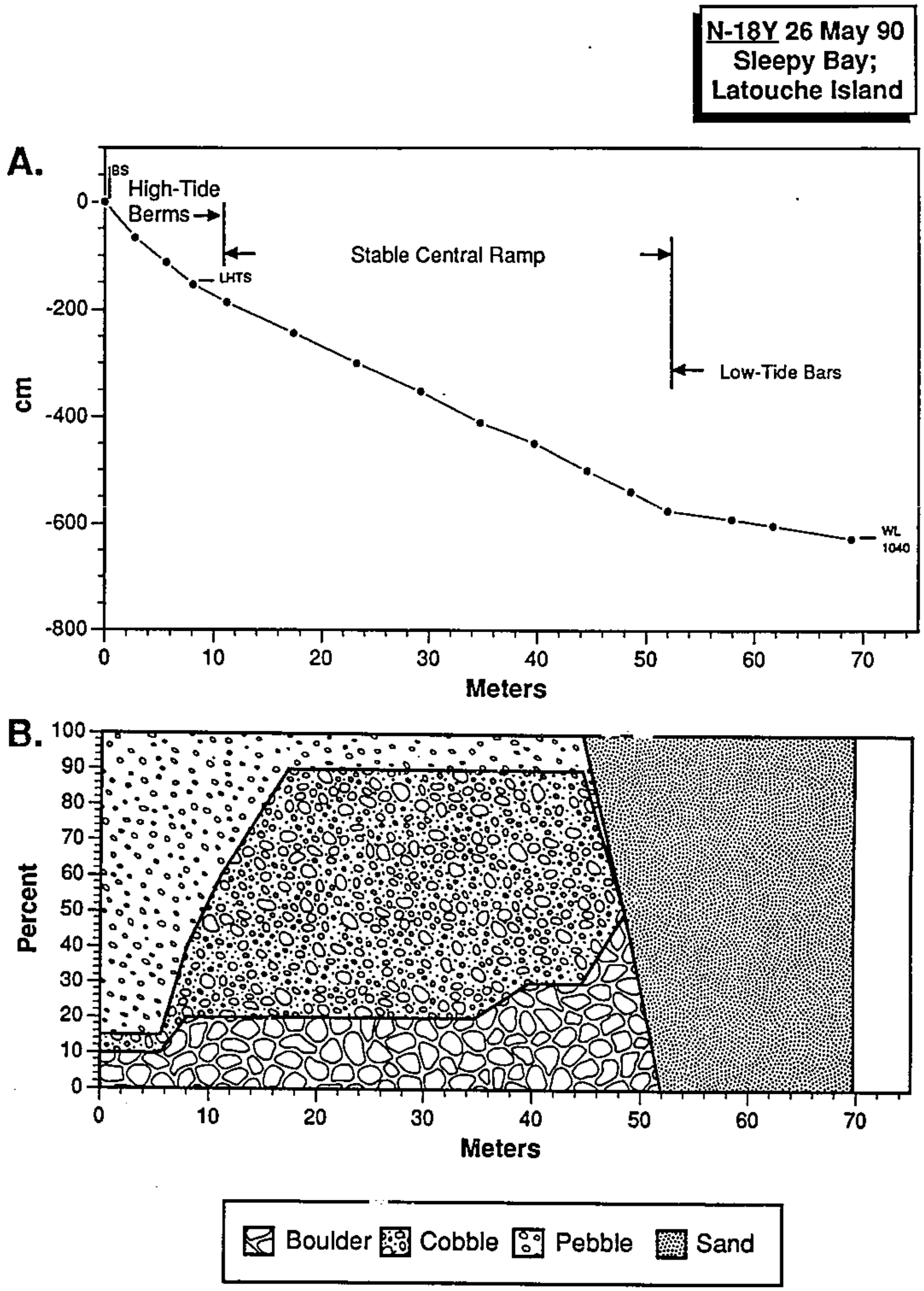


FIGURE 76. Station N-18Y on 26 May 1990.

A. Topographic profile. No major surface features occur along the profile, which is characterized by three distinct seaward slopes, with the beachface in the high-tide berms area being steepest (11°) and the surface on which the low-tide sand bars occur being flattest (1°).

B. Surface sediment distribution map based on estimates at each of the survey points (circles on A). Pebbles dominate the high-tide area, cobbles the central ramp, and sand the low-tide region.

3) Low-tide bars

This portion of N-18 was reached only during two of the fall and winter surveys. Intertidal swash bars were encountered during the surveys of 1 February 1990, 24 May 1990, and 5 September 1990. This zone, which dips offshore at a low angle (3°), has the potential for significant change as it is a part of the delta complex of the stream.

The beach profile at station N-18 was surveyed 8 times (see Table 4). Except for the profiles run on 4 January 1990 and 1 February 1990, no surveying errors were found. The angle of the 4 January 1990 transect was 5° off, and the 1 February 1990 survey plotted an average of around 50 cm lower than the profiles that preceded and followed it. The exact overlap of the upper part of the central ramp portion of the profiles during the 19 September 1989 and 5 September 1990 surveys (Fig. 77F) led us to believe that the 1 February 1990 survey was in error, thus we discounted it.

The complexity of the changes that have occurred at profile N-18 is shown on Figure 77. A well-defined, "heavily oiled gravel berm" was present at the 6 m mark on 19 September 1989 (Fig. 77A). This berm was obliterated during the high spring tides of mid-October and the profile was smooth and featureless during the 20 October 1989 survey. By the time of the 6 November 1989 survey, a new complex spring-tide berm that was around 30 cm high and composed mostly of pebbles (called "multiple berms" in field notes) had formed at the 8 m mark. The survey on 5 December 1990 showed that the spring-tide berm had moved further up the profile and that a "coarse cobble bar" had developed over the lower part of the central ramp (21-25 m; Fig. 77C). This new feature was probably similar to the berm-like ridges we found on some of the other stations (e.g., N-15). Michel states in the field notes of 5 December that toward the creek (away from profile) the "surface appears to have been eroded heavily, leaving cobbles/boulders exposed". The eroded material presumably moved over onto profile N-18. Significant changes were again noted during the 4 January 1990 survey, which showed that the spring-tide berm moved landward another 3 m and a new, complex lower-level (neap?) berm had formed near the 8 m mark. According to the survey data, the lower central ramp and upper part of the low-tide bar components of the profile were lowered about 30 cm during this interval (Fig. 77D).

FIGURE 77. (Facing Page) Overlay plots of the beach profiles measured at station N-18.

A. (19 September 1989 to 20 October 1989) Beach was flattened during high spring tides of mid-October.

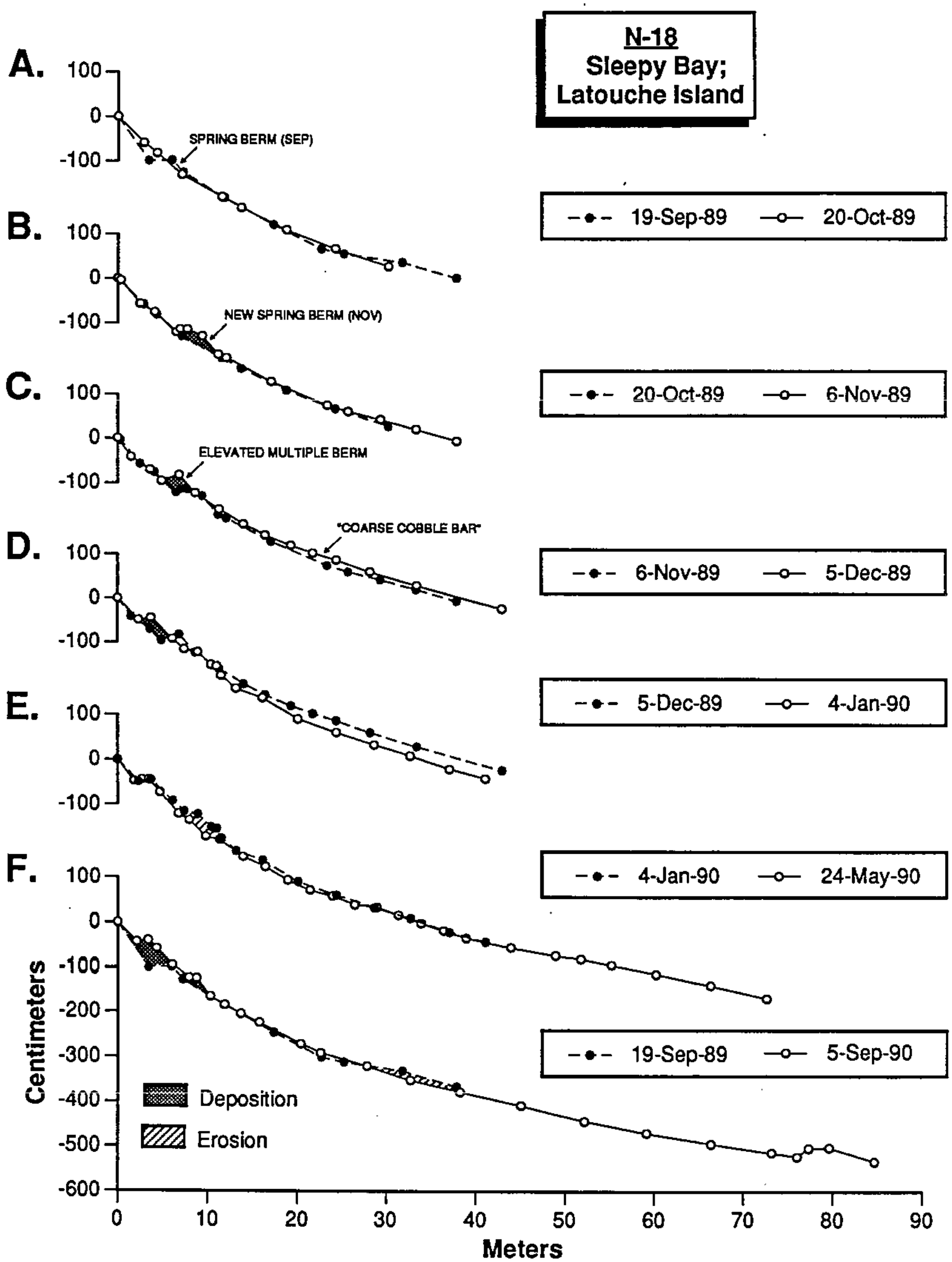
B. (20 October to 6 November 1989) A new spring-tide berm, composed mostly of cobbles, had formed.

C. (6 November 1989 to 5 December 1989) The spring-tide berm was moved higher up the profile and a "coarse cobble bar" (berm-like ridge) was constructed over the lower portion of the stable central ramp.

D. (5 December 1989 to 4 January 1990) Cobble "bar" was eroded away and the old spring berm was elevated even further. New spring berm formed around 8 m mark.

E. (4 January 1990 to 24 May 1990) Lower spring berm was eroded away and rest of profile remained the same.

F. (19 September 1989 to 5 September 1990) Two major areas of change are highlighted: 1) deposition on the berms, and 2) erosion on the lower part of the central ramp.



N-18
Sleepy Bay;
Latouche Island
A.
B.
C.
D.
E.
F.
SPRING BERM (SEP)
NEW SPRING BERM (NOV)
ELEVATED MULTIPLE BERM
"COARSE COBBLE BAR"
19-Sep-89
20-Oct-89
20-Oct-89
6-Nov-89
6-Nov-89
5-Dec-89
5-Dec-89
4-Jan-90
4-Jan-90
24-May-90
19-Sep-89
5-Sep-90
Deposition
Erosion
Centimeters
Meters

As pointed out above, we believe the 1 February 1990 survey is off mark, but, in fairness, we note the following from the report to NOAA by Sexton, Gibeaut, and Balcom (1990; p. 80):

> "The beach had experienced a net lowering of 20-30 cm by February 1990. This lowering of the beach is a major factor in the lateral movement of the small stream toward the station on the intertidal beach face. By February, the entrance of the stream at the bay was only 10-20 m from the station line. There was also a moderate-sized swash bar that had moved onto the lower beach which was obviously associated with this small inlet."

We believe the February survey was offline, partly because of the heavy snow. The stream probably migrates to the east because sediment is piling up on its west side as a result of longshore sediment transport from west to east.

The overlay plots for the 4 January 1990 and 24 May 1990 survey (Fig. 77E) shows that the lower level berm that was present in January was missing in May. The high-level, spring berm had not changed. Much of the story of change on profile N-18 is told by the overlay of the plots for 19 September 1989 and 5 September 1990 (Fig. 77F), which illustrates berm formation and migration at the top of the profile and lowering of the lower part of the central ramp. Missing is a demonstration of the migration of swash bars on the lower levels of the profile.

The previous discussion shows that sediment was almost continuously in motion on station N-18. However, the sediment envelopes generated were relatively thin. Vertical change of around 50 cm occurred frequently in the area of the high-tide berms, little vertical change occurred on the upper part of the central ramp, whereas vertical changes probably up to 50 cm occurred on the lower part of the central ramp. The motion on the lower part of the central ramp was both depositional and erosional, with a resulting net erosion. Our data are sparse for the low-tide bar area, but migrating swash bars with slip-faces up to 50 cm in height are a possibility. The primary sediment transport direction appears to be west to east, judging by: 1) orientation of mouth of stream (Fig. 74A); 2) passage of erosion zone by N-18 in west to east direction; and 3) accumulation of a sand bar on the low-tide terrace to the east of the stream mouth (observed on 26 May 1990).

The mobility of the sediments is further demonstrated by the speed with which the beach-profile sediments returned to a natural appearance after very extensive mechanical reworking on several occasions in both 1989 and 1990. Much by September, most evidence of this extensive disruption had disappeared, even with the summer wave conditions.

The morphology of station N-18 differs somewhat from profiles N-18X and N-18Y, which are illustrated in Figures 75 and 76. Station N-18X, located to the west of the stream mouth (Fig. 72), has a larger high-tide berm complex, but no visible swash bars in the low-tide area. Station N-18Y, which is located east of N-18, has no conspicuous high-tide berms, and is coarse-grained overall, except for the sandy low-tide bars. The central ramp is expanded in length on N-18Y. These differences occur because N-18X was run across the depositional lobe of the delta, and N-18Y is located almost out of the realm of influence of the delta, near the rocky talus slope that flanks the eastern arm of the bay.

Sediments. The sediments on the beaches at the head of Sleepy Bay are derived from two sources: 1) the rocky headlands located within and to either side of the bay; and 2) the stream and its delta. The coarse clasts, which are quite hard and resistant to breakage, are composed primarily of dark-colored metamorphosed sandstone and shale, and basaltic lava.

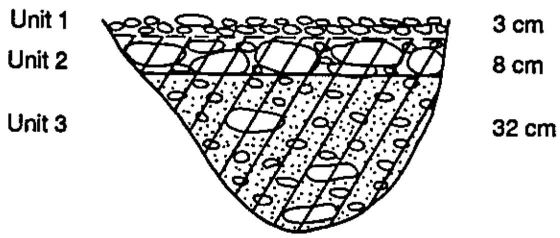
A map of the general grain size of the surface sediments at the head of Sleepy Bay is presented in Figure 72, and the surficial sediment plots for the three profiles are given in Figures 73C, 75C, and 76C. The surface sediments of profile N-18X are dominated by cobbles throughout, with pebbles being more abundant on the high-tide berms. Boulders, which are scarce on the profile, making up only 10 percent, are most abundant on the stable central ramp. Surface sediments on profile N-18 are made up of an average of 50 percent pebbles, which are most common on the high-tide berms. Boulders, again, are present mostly on the stable central ramp, where they never exceed 20 percent of the total. Profile N-18Y is quite different, with pebbles dominating the upper profile and sand the lower part of the profile. Cobbles compose more than 50 percent of the surface material on the stable central ramp, and boulders average over 20 percent of the total.

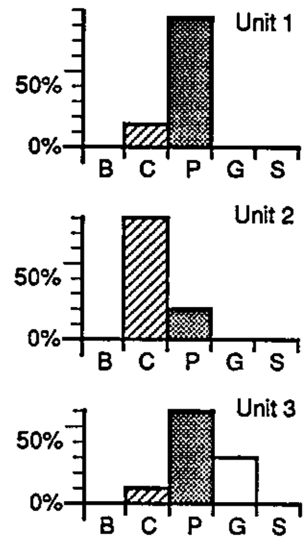
A total of 29 trenches were dug at the head of Sleepy Bay, and two of the trenches dug on 24 May 1990 are given in Figure 78. Armoring is poorly developed at this site compared to others in PWS, the sediments at depth being only slightly finer than the surface layer. This distribution probably is a function of the finer-grained, more mobile character of the sediment. However, this beach sediment was

N-18 SLEEPY BAY, 24 MAY 1990

- Oiled Zone

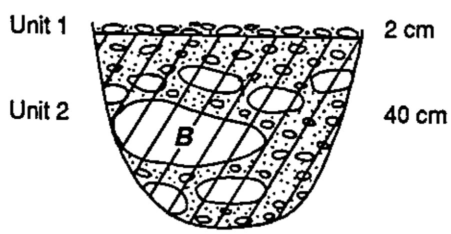
TRENCH A

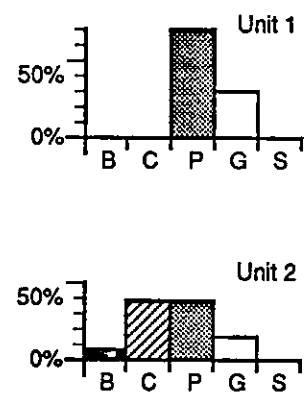




Unit 2: Heavy mousse coating, medium brown
Oiled layer of spruce needles at top
Unit 3: Light mousse coating, medium brown
Scattered wood and spruce needles

TRENCH B





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

FIGURE 78. Description of two trenches dug on profile N-18 on 24 May 1990. See Figure 73B for location. Note absence of armoring and abundance of subsurface oil.

mixed significantly during cleanup in the summer of 1989, and it is possible that there has not been enough time for the armoring process to have matured.

Oil Distribution Patterns. The surface oil distribution at Sleepy Bay is shown in Figure 79. Initially, the surface oil covered 100 percent of the upper 20 m of the shoreline, as a heavy coating on all clasts. After the October storm and high tides, the oil had been eroded from this zone and pushed higher up the beach. Continued erosion, deposition, and migration of the high-tide berms at neap-to-spring tide levels reworked the surface sediments so that the heavy oil coating was quickly reduced to a thin film, except for on the larger boulders and the zone of oiled debris high up the beach. This high zone of oil was covered with snow during the 4 January 1990 survey. The oil histograms of Figure 79B show this steady reduction of surface oil as the sediments were continuously reworked. The TPH analyses of surface sediments in Table 12 show that very low levels of oil have occurred at Sleepy Bay since December 1989. The samples collected in November were from the top 5 cm, whereas most of the others represent 0-2 cm.

The subsurface oil distribution was much more complicated, as shown in Table 12. In spite of the extensive reworking of the top 50 cm at the high-tide berms, samples from the top 25 cm still contained significant amounts of oil, ranging from 200 to 2,000 ppm. Visually, the upper 25 cm was always described as having light-to-moderate oiling, with a deeper zone with heavier oiling (Fig. 74B). The >25 cm deep samples listed in Table 12 from the high-tide berms were usually collected at 40-50 cm depth. These sediment samples usually had high TPH levels, ranging from 12,550 ppm in September 1989 to about 4,000 ppm in February and September 1990. This deeper zone of oil could be a source from which oil is transported into the overlying but shallower sediments; alternatively, oiled sediments eroded from the profile could be buried as the berms migrate up the beach. There must be a source of oil which continues to contaminate the shallow subsurface sediments even though they are frequently reworked.

That large amounts of subsurface oil remain in the stable central ramp is evident from the data shown on Table 12. The highest TPH concentration measurement at Sleepy Bay was 25,000 ppm, for a sample collected in September 1989 from 30-33 cm depth, which was representative of the zone from 5-35 cm. In February 1990, a sample from 15-20 cm contained 12,290 ppm TPH. Since this zone is relatively stable, that is, there has been no regular cycle of erosion/deposition, the oil concentrations are likely to be reduced only by tidal/freshwater flushing and

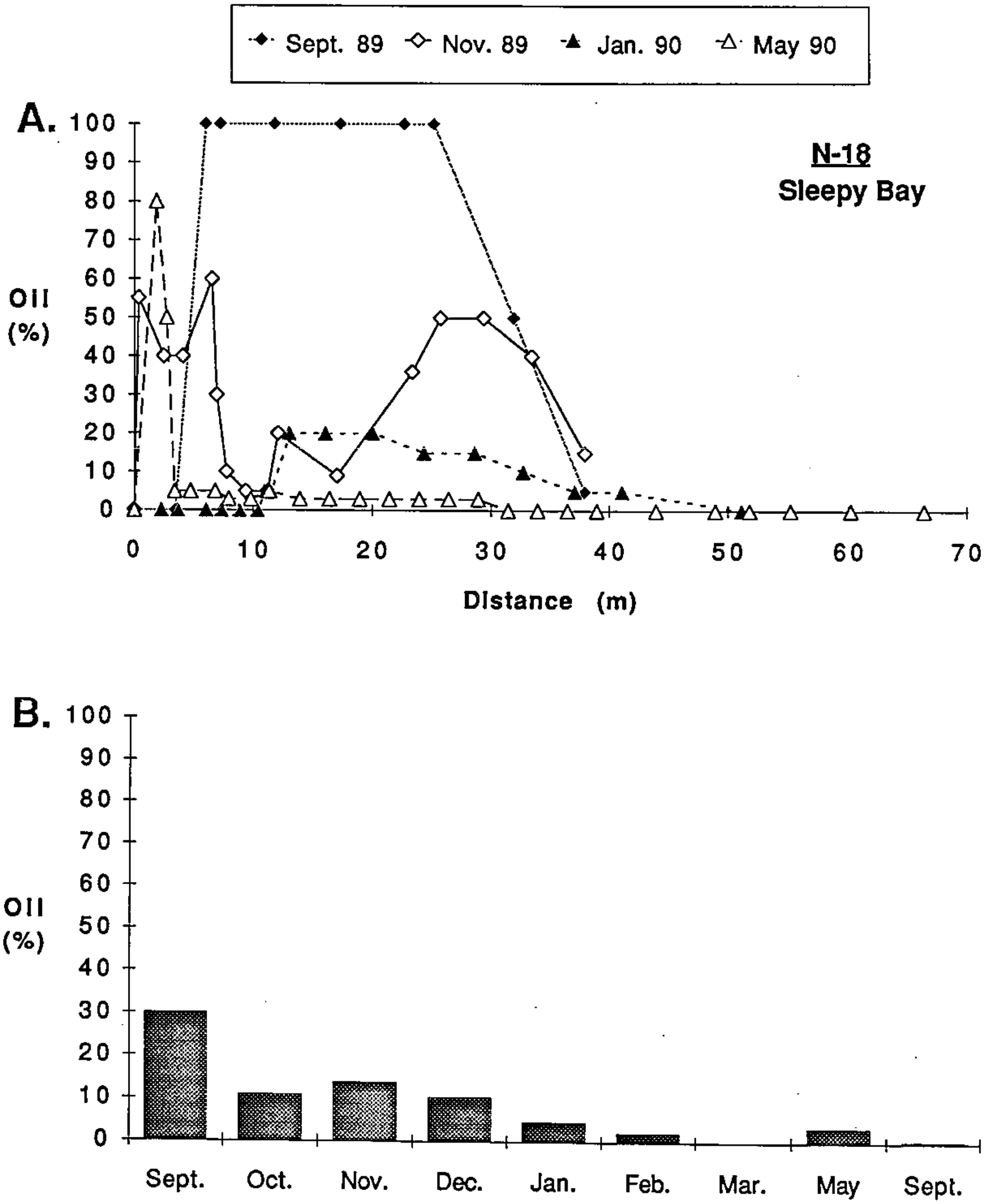


FIGURE 79. Plots of the percent coverage of surface oil along profile N-18 in Sleepy Bay.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 12. Sediment TPH (in ppm) for N-18 on Sleepy Bay by morphological zone.

Surface Samples

Date	High-Tide Berms	Stable Central Ramp	Low-Tide Bars
9/89	800		
10/89		240	
11/89	420	740/1,000/4,520	
12/89		70	
1/90	80	160	10
2/90		30	

Subsurface Samples

	High-Tide Berms		Stable Central Ramp		Low-Tide Bars	
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	< 25 cm	> 25 cm
9/89		12,550	3764/9,320	2,010/18,670	970	103
10/89	980/1,050	490/5,960		1,580		
11/89	1,480	290		11,150/15,620		
12/89	220	2,730		360/5,770	50	
1/90		490	1,620	580/5,110		
2/90	2,070	3,870	1,250/12,290	10/24,080	<10	10
9/90		4,050		25,010		

biodegradation. At least one erosion event has affected this zone; the removal of 30 cm of sediment as shown on Figure 77F brought the heavily oiled sediments closer to the surface. But it could take many years for this stable ramp to be eroded down to the maximum depth of the oil, which was still 40-50 cm below the present surface of the central ramp as of September 1990. The extent to which the persistent subsurface oil near N-18 is a direct result of, or exacerbated by, the spreading of oiled sediments excavated from the stream bank is unknown. Our recollection is that the sediments were not placed directly on NOAA's profile, and the surface did not appear to be disturbed (although the surface sediments are quickly reworked into a natural profile). The sediment distribution with depth is not unusual. Oiled sediments could have been transported into the area from the spread-out piles, but the area has shown net erosion, not deposition. Nevertheless, Sleepy Bay remains one of the most heavily oiled shorelines in PWS and poses numerous cleanup problems.

The lower part of the profile, where the low-tide bars and delta platform occur (Fig. 72), showed oil contamination with 970 ppm at 10-15 cm, in September 1989, but very low levels thereafter (Table 12). Any fine-grained sediment that was washed into this zone as a result of shoreline treatment was quickly mobilized. However, there is a good potential for transport of oiled sediments into the subtidal zone which contains steep rocky ledges.

It should be noted that Sleepy Bay is a complex area, with abrupt lateral changes in sediment type, exposure to waves, nature of oil contamination, and treatment applied along the shoreline. Therefore, the stations being monitored by the various research groups are not directly comparable. It is generally agreed, however, that Sleepy Bay has high potential for long-term persistence of subsurface oil. It was the leading candidate site for rock washing in 1990 because of this heavy residual oil. Most of the high-tide berms were extensively excavated and relocated in August/ September 1990 in an attempt to facilitate reworking by storm waves. Because of the mobility of the finer-grained sediments, recovery of the beach profile should be relatively quick. However, berm relocation has done little to address the heavy oil remaining in the central part of the profile.

Observations on Biota. This station has been included in the NOAA intertidal biology monitoring program. Two quadrat elevations were worked about 5 m west of the N-18 profile line. The mid-zone quadrats are on the lower stable central ramp and the low-zone quadrats are in the transition zone to the low-tide bars.

Both quadrat locations looked free of oil and any signs of physical disturbance in May and September 1990. The low quadrats are adjacent to the area used in 1989 to excavate clean sediments for placement along the stream. The equipment could have tracked over the sites while maneuvering around. Also, it should be noted that the fresh-water discharge from the stream affects both sites.

Station N-14

Introduction. Station N-14 is located at the head of the western arm of Northwest Bay on the shoreline of Eleanor Island. This arm of the bay, which is oriented north-south, is about 2.3 km long and it has a very narrow entrance of less than 0.5 km. Sediments are >50 percent pebbles throughout the profile, with liberal quantities of granule material. The profile is sandwiched between two small anadromous streams, which are no doubt the primary source of the finer sediment. The lower part of the profile was usually host to slowly migrating pebble swash bars throughout most of the survey. We consider the bars to be components of a subtle delta built by the two streams. The entrance to this arm of Northwest Bay has an effective fetch of 27 km in a northerly direction, but the narrowness and length of the arm serves to dampen the storm waves entering from the north, the only possible entrance. Consequently, wave conditions are mostly mild at the head of the bay. This area was uplifted 1.2 m during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the profile on 23 May 1990 are given in Figure 80 and selected photographs are presented in Figure 81.

All of Northwest Bay was heavily oiled early in the spill, and it was the focus of a long and intensive cleanup starting in early May. It was one of the first areas treated by the crews, and thus it probably took more abuse as the crews learned from their mistakes. One of the biggest problems was the frequent escape of sheen under the containment booms (Fig. 81) and reoiling of treated shorelines. Therefore, many shorelines received multiple washing with LCV systems. The smaller LCV systems were used because of the small size of the bay and the wide intertidal zone at the bay head. The LCVs were anchored at about mid-tide and allowed to rest on the tidal flat at the lower tidal levels. There was also extensive flushing of oiled sediment into the lower intertidal and subtidal zones during the washing activities, especially at the bay head.

Morphology and Beach Dynamics. Three very distinct components make up this station:

1) High-tide berms

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

N-14 23 May 90
NW Bay; West Arm

A.

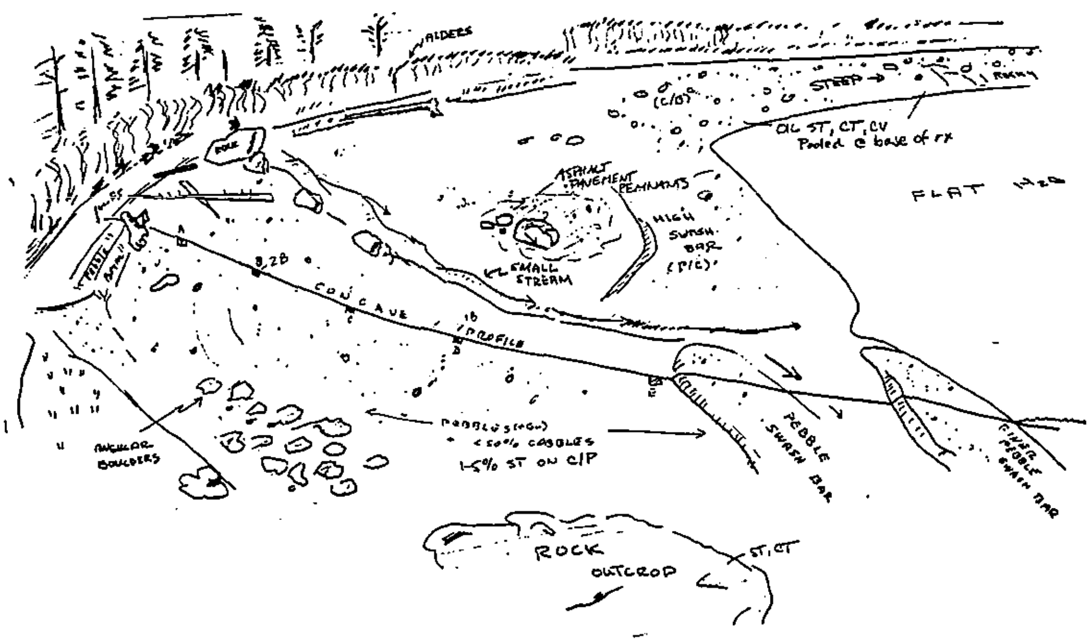
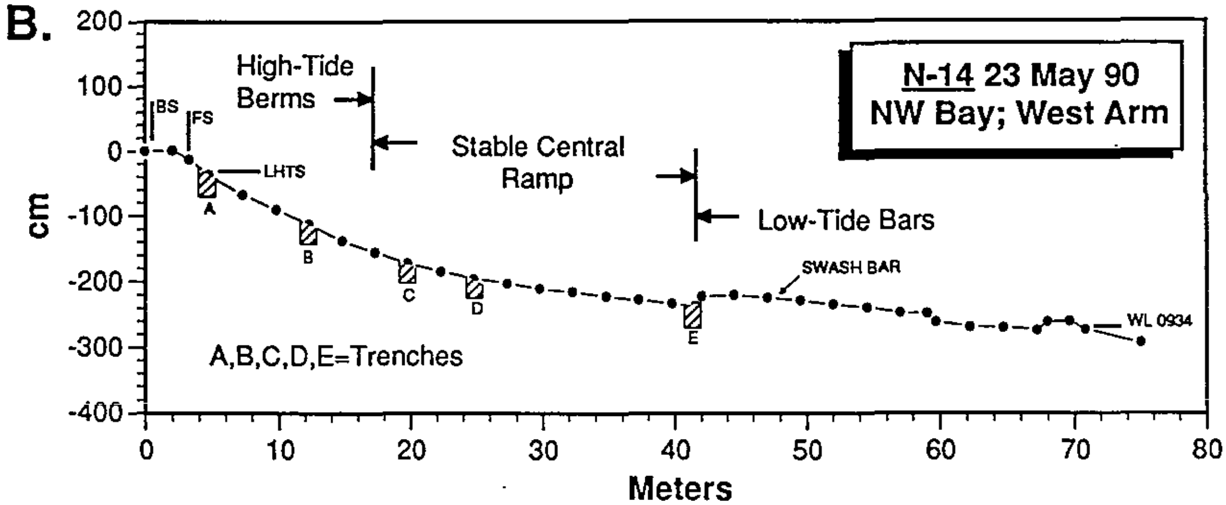


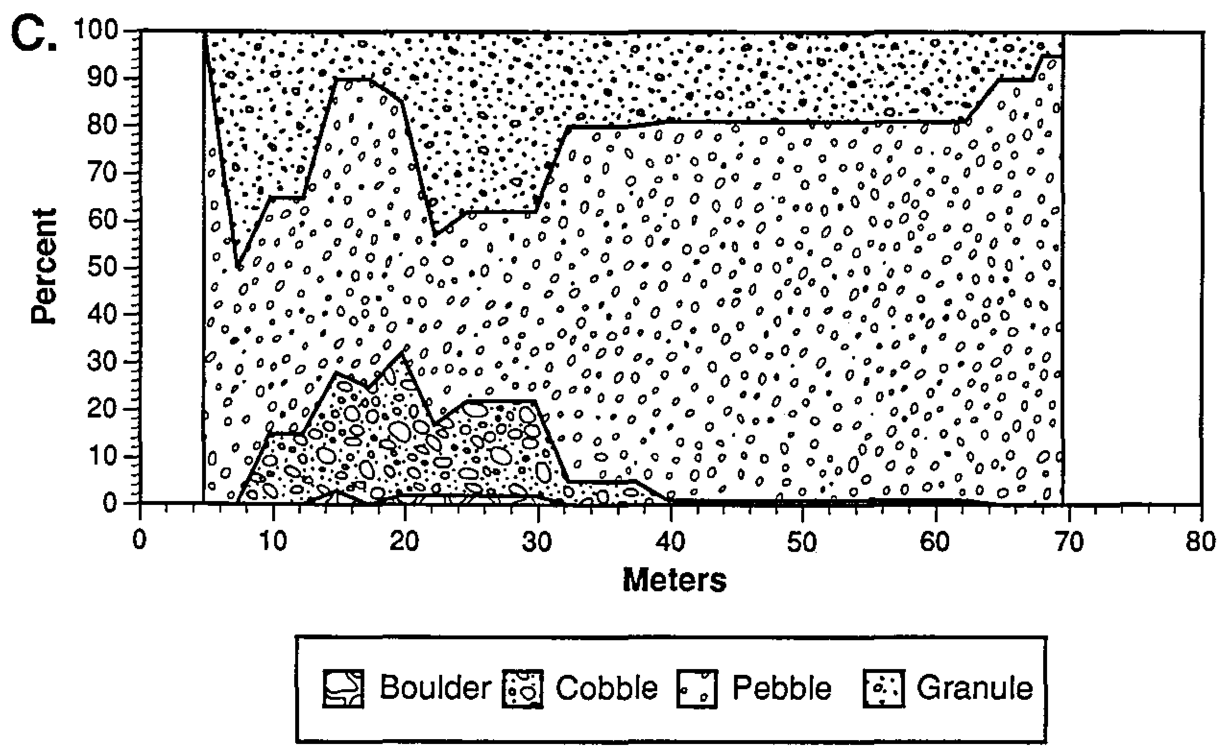
FIGURE 80. Station N-14 on 23 May 1990.

A. Field sketch. Note small berms at the top of the beachface, the concavity of the central ramp, and the presence of two well-defined, pebble swash bars. The small outbuilding of sediment at this locality is a result of deposition by two small streams.

B. Topographic profile illustrating the contrasting slopes of the three primary components of the station. The larger swash bar had migrated landward about 3.5 m since 2 February 1990.

C. Surface sediment distribution pattern based on estimates of grain size at 30 of the survey sites indicated by circles on the profile plot (B). Pebbles, which are most common on the low-tide bars, are the dominant sediment type, with cobbles and boulders occurring primarily on the stable central ramp.


B.
N-14 23 May 90
NW Bay; West Arm
High-Tide Berms
Stable Central Ramp
Low-Tide Bars
BS
FS
LHTS
SWASH BAR
WL 0934
A,B,C,D,E=Trenches
cm
Meters


C.
Percent
Meters
Boulder
Cobble
Pebble
Granule

2) Stable central ramp

This part of the profile, which is the coarsest grained of the three components, even containing some boulders, has a distinct concave-upward shape, which signifies a historic erosional pattern. Changes were very slight during the survey period, however. The ramp slopes seaward at 2°.

3) Low-tide bars

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

The profile at station N-14 was surveyed only six times during the study. The overlay plot of the surveys of 19 September 1989 and 4 September 1990, which is given in Figure 82, shows that middle and upper portions of the profile changed a relatively small amount during that interval. Two of the more critical profiles, those run on 2 February 1990 and 23 May 1990, apparently were not run along the same line as the two September profiles. However, there can be no doubt that this profile is slow to change, except in the area of the low-tide bars. The first swash bar surveyed, which had a slip face 7 cm high, occurred near the 43 m mark on 8 December 1989. It was still close to the same position during the 28 February 1990 survey, but had increased somewhat in size, the slip face being 8 cm in height. A smaller bar about 5 cm in height was located under water 10 m further offshore. By the time of the 23 May 1990 survey, the most landward swash bar migrated about 3.5 m (Fig. 80B). It had a slip face 14 cm high. The field notes state that a mussel bed had been buried by the migrating swash bar. The stream outlet had eroded through the region where the second bar was located on 28 February, and a new bar with a 12 cm high slip face had formed about 8 m further offshore.

Although the finer sediment at station N-14 undergoes considerable transport, the foregoing discussion and the data of Figure 82 show that the potential for the development of a significant sediment envelope on this profile is slight except in the area of the low-tide bars. Between September 1989 and September 1990, a maximum thickness of 30 cm of deposition took place at the top of the beach face. Erosion ranging from 5-20 cm occurred along most of the central ramp, and this has probably been an ongoing process for some time, judging by the concave-upward shape of the profile. The greatest potential for maximum development of sediment envelopes occurs on the lower part of the profile, where migrating swash bars and their accompanying swales move sediments in a vertical range of at least 30 cm. It is probable that sediments are transported from west to east along this beach, judging by the orientation of the swash bars, but the rate of migration is probably very slow, with the principal sediment motion being onshore and offshore. It is possible that the large swash bars have formed as a mechanism for transporting the sediment washed downslope during the cleanup activities back up onto the beach. That is, the sediment removed during the 1989 treatment has not made it back up to the high-tide berms, but instead comprises the swash bars. Reconstruction of the original beach requires the occurrence of constructional waves that will push the granules and pebbles back up the beach. Obviously, such waves are rare in the very sheltered head of Northwest Bay.

Sediments. Sediments along this bay head are derived from the erosion of adjacent headlands by waves and from deposition by the two streams. The streams are no doubt the primary source for most of the finer components of the sediment suite. The rocks of Eleanor Island are mostly basaltic lava flows and intrusives associated with sedimentary rocks, chiefly basalt and diabase (Moffit, 1954).

The surface sediment distribution along the profile on 23 May 1990 is given in Figure 80C. The high-tide berms are covered primarily by pebbles and granule material (roughly 50/50). Cobbles and boulders occur almost exclusively on the slightly eroding central ramp, with boulders composing less than 5 percent. Pebbles dominate the surfaces of the low-tide bars, with granules averaging around 20 percent.

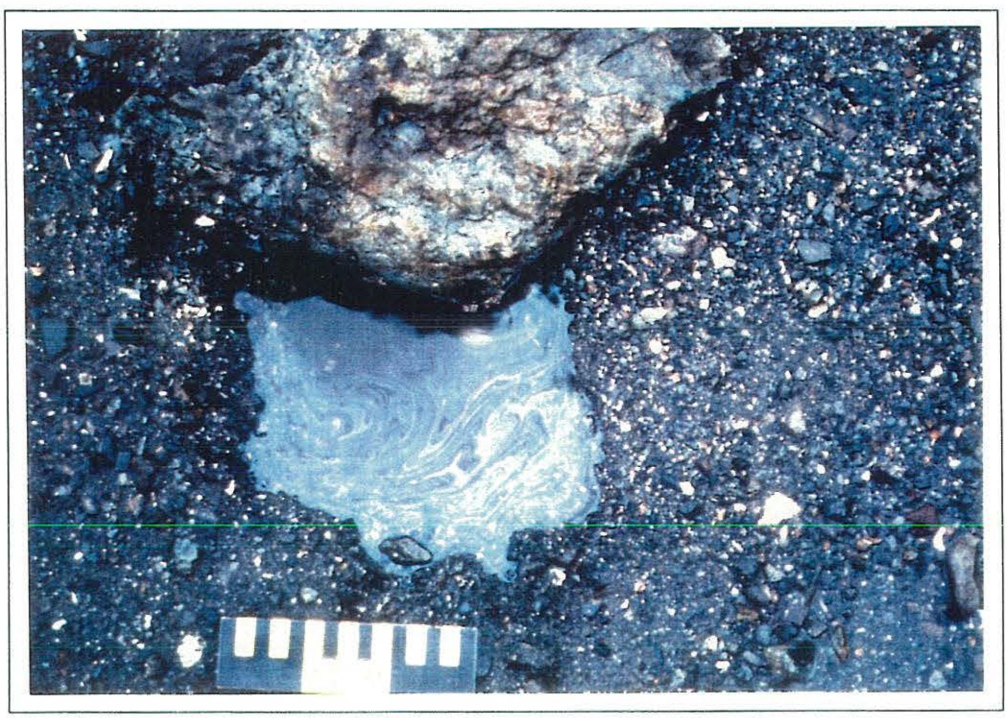
FIGURE 81. (Facing Page) Photographs of station N-14.

A. Cleanup activities at the head of West Arm of Northwest Bay in mid-June 1989. This area was cleaned extensively. Note sheens escaping booms. Location of profile N-14 is shown. Photo by J. Michel.

B. Silver sheens on the water table in a depression left after turning over a boulder on the central ramp on 8 December 1989. The surface and subsurface sediments otherwise were mostly clean. Photo by D. Hall.

A.

B.



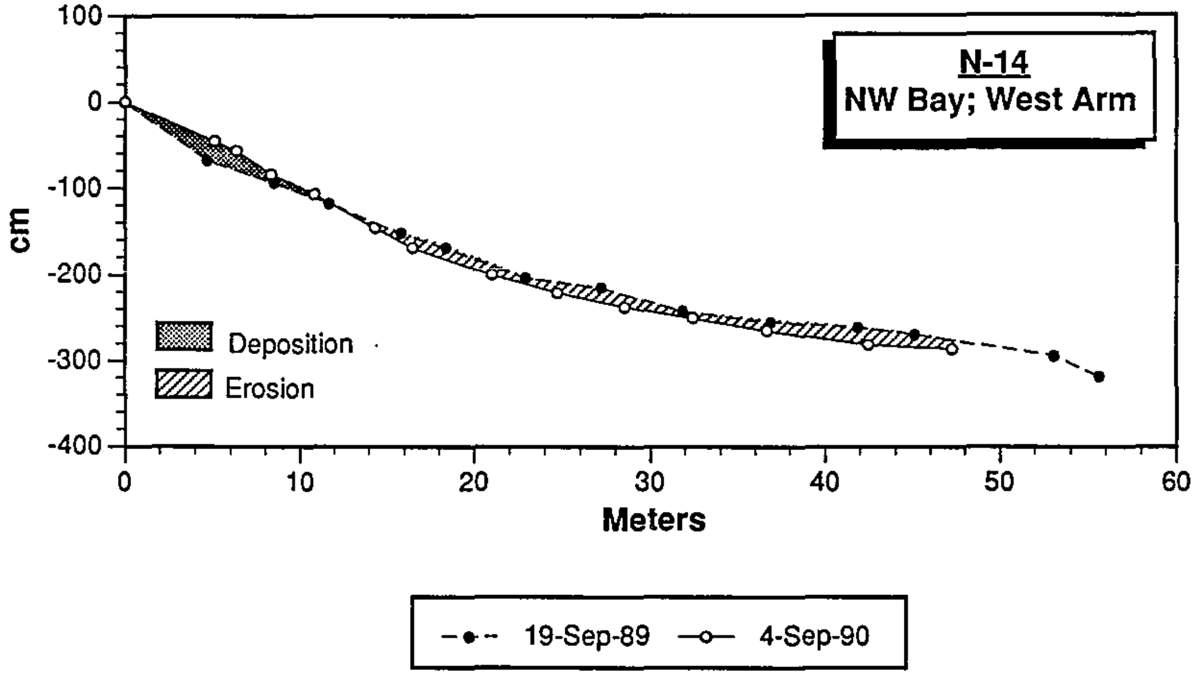


FIGURE 82. Changes at station N-14 over a one-year period. Note relatively minor accretion at the top of the beachface and minor erosion on the central ramp. The tide was too high to reach the low-tide bars during either of these surveys.

A total of 20 trenches were dug on this beach. Armoring is not well developed, probably because of the lack of the coarser gravel components and the relatively low wave action. Also, this section was washed heavily in the summer of 1989, thus the sediments may not have regained their former structure. A substance called "peat" was encountered at depths of 16-18 cm in several trenches dug on the central ramp during the 19 September 1990 survey.

Oil Distribution Patterns. The surface sediments along the profile looked deceptively clean in September 1989, except in two areas. Oiled wrack covered the high-tide zone and there was a 5-m wide band of 100 percent oil cover about midway down the central ramp (Fig. 83). However, surface sediment samples from all three zones contained over 1,000 ppm TPH (Table 13). The surface oil on the central ramp decreased by half in October but persisted through December, with significant reduction thereafter. Most of the remaining surface oil occurred as a stain on the larger pebbles and cobbles, which occurred throughout the profile. No samples from the summer surveys have been analyzed, but less than 5 percent stain was reported in May and no surface oil was observed during the September 1990 survey (Fig. 83). Heavily oiled areas were observed adjacent to the profile, most notably a large asphalt pavement to the west which was manually removed in 1990 (Fig. 80A). The rocky shoreline on both sides of the bay also remained oiled. Sheens were commonly observed on the water table when large cobbles were turned over (Fig. 81B). It appears that oil being released from these areas tends to adhere to the granule sur-face sediments, thus the measurement of 400 ppm TPH in a surface sample from the low-tide bars in February.

There appears to be minimal contamination of subsurface sediments (Table 13). A discontinuous oiled layer at 5-10 cm below the spring berm was found to contain over 6,500 ppm TPH, but the layer was never observed again. A sample taken at 40-45 cm in the same trench contained 20 ppm TPH. The only other highly oiled sample was taken at 50 cm depth in September and contained 1,090 ppm TPH. This sample was below a discontinuous "peat" layer, so it probably represents the limit of reworking of the sediments during shoreline treatment activities. All other subsurface samples collected after September 1989 had less than 100 ppm TPH, with most containing 20 ppm or less. Therefore, the sediments are relatively clean with depth. However, in December 1989, sheens were observed in groundwater rills draining the area near the asphalt pavement and silver sheens under the larger cobbles and boulders (Fig. 81). Trace sheens were again reported in February, but,

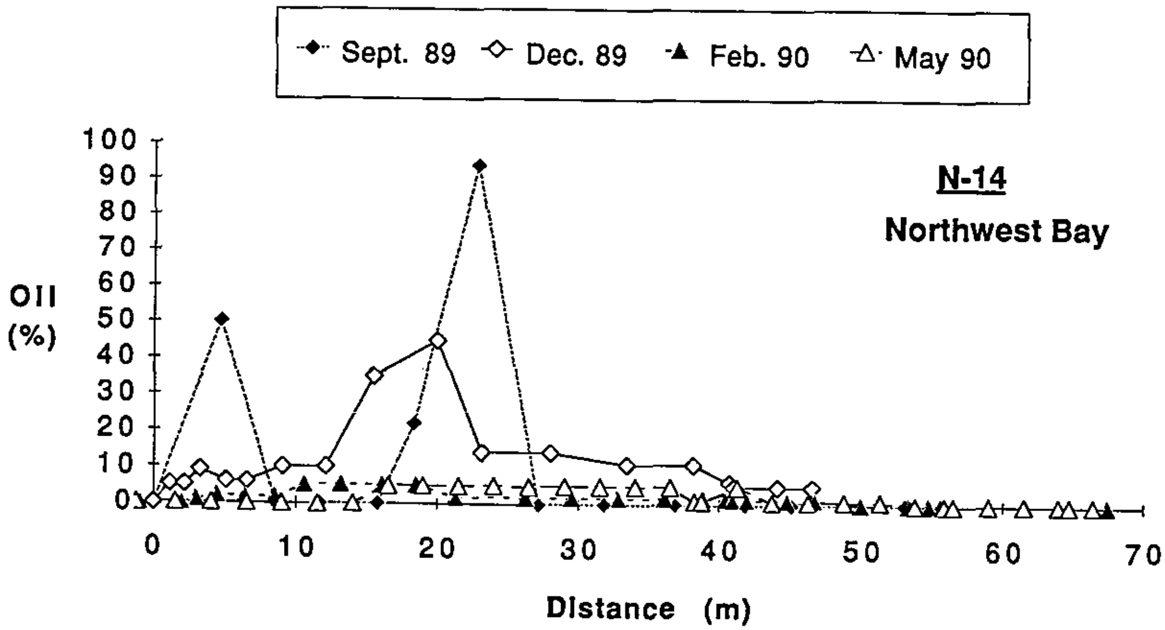


FIGURE 83. Plots of the visual estimates of surface oil distribution at station N-14 in Northwest Bay for selected surveys. The oiled wrack at the high-tide line was removed after 19 September 1989, but the oil on the central ramp persisted all winter.

thereafter, the sediments appeared to be clean. Any continuing contamination of this site is probably a result of reoiling of surface sediments as oil is flushed from adjacent areas, a process which should slow as the oil continues to weather.

Observations on Biota. It should be noted that the NOAA biological monitoring quadrats are located west of the profile and in a different physical setting. The quadrats are sited in a zone which is positioned between the fine-grained bayhead beach and the steep rocky rubble western shore. The surface is composed of a cobble armor on a relatively gentle slope. There is little comparison between our profile and these quadrats except for the low degree of exposure to wave activity.

TABLE 13. Sediment TPH (in ppm) for N-14 in Northwest Bay by morphological zone.

Surface Samples

Date	High-Tide Berms	Stable Central Ramp	Low-Tide Bars
9/89	30/1,050	220/720/1,140	270/1,450
10/89	130	340	
12/89		80	100
2/90	130	110	240/400

Subsurface Samples

	High-Tide Berms		Stable Central Ramp		
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	Low-Tide Bars
9/89		<10		50/220/1,090	10/10/20/190
10/89	130/6,520	20	20/70		
2/90	<10	20	20		40

PEBBLE BEACHES WITH TIDAL FLATS

General Description of Shoreline Type

There are a number of sheltered pebble beaches with associated tidal flats scattered throughout the study area. Wave energy is relatively low in these areas, with the pebbles at the high tide zone being mobilized by the occasional storm. The sediment veneer is usually quite thin, with peat being a common substrate under the sediment cover. The tidal flats typically have a rich biological assemblage, including clam and eelgrass beds. There are three NOAA permanent stations located on shorelines of this type—stations N-8 and N-9 on Block Island and station N-11 on Crafton Island.

Station N-8

Introduction. Station N-8 was located on a tombolo washover terrace that connects two islands, Block and Eleanor, which were separate islands before the 1964 earthquake. Uplift of around 1.2 m raised the sea floor to the point where the gravel-based bar could connect the two islands.

Once the tombolo formed, a new bayhead beach facing south-southeast was created. The new bay is about 1 km long and it has an effective fetch of 3 km in a south-southeast direction (down its length) to Sphinx Island. However, a relatively unobstructed effective fetch of 25 km extends from the mouth of the bay to Montague Island. In order for waves generated along that fetch line to reach the head of the bay, they would have to be refracted in a complex manner. Thus, although wave action does occur at the site, it is mild under most conditions.

A fuel dump to support cleanup activities was established on the washover terrace over the 1989 winter, making it difficult to maintain the station. The back survey markers were destroyed after the 17 September 1989 survey and again before the 4 March 1990 survey. The station was not surveyed again after the attempt on 4 March 1990. The beach showed only minor changes in the form of high-tide berms throughout the study period, except for a major overtopping of the terrace during the high spring tides of mid-October 1989. A field sketch and beach profile for station N-8 on 7 November 1989 are given in Figure 84.

This site was heavily oiled as slicks passed along the eastern coastline of Eleanor Island in late March 1989. The tombolo's upper surface provided an easy landing site for helicopters, and thus it was used frequently to access the shore and meet water-based crews in the area. Hot-water washing was used in 1989, followed by bioremediation. Block Island became the major fuel depot for helicopters in 1990, with the construction of four wooden landing platforms, boardwalks, toilets, etc. Although the fuel tanks were contained, spills did occur and thus sampling of this site was terminated after March 1990.

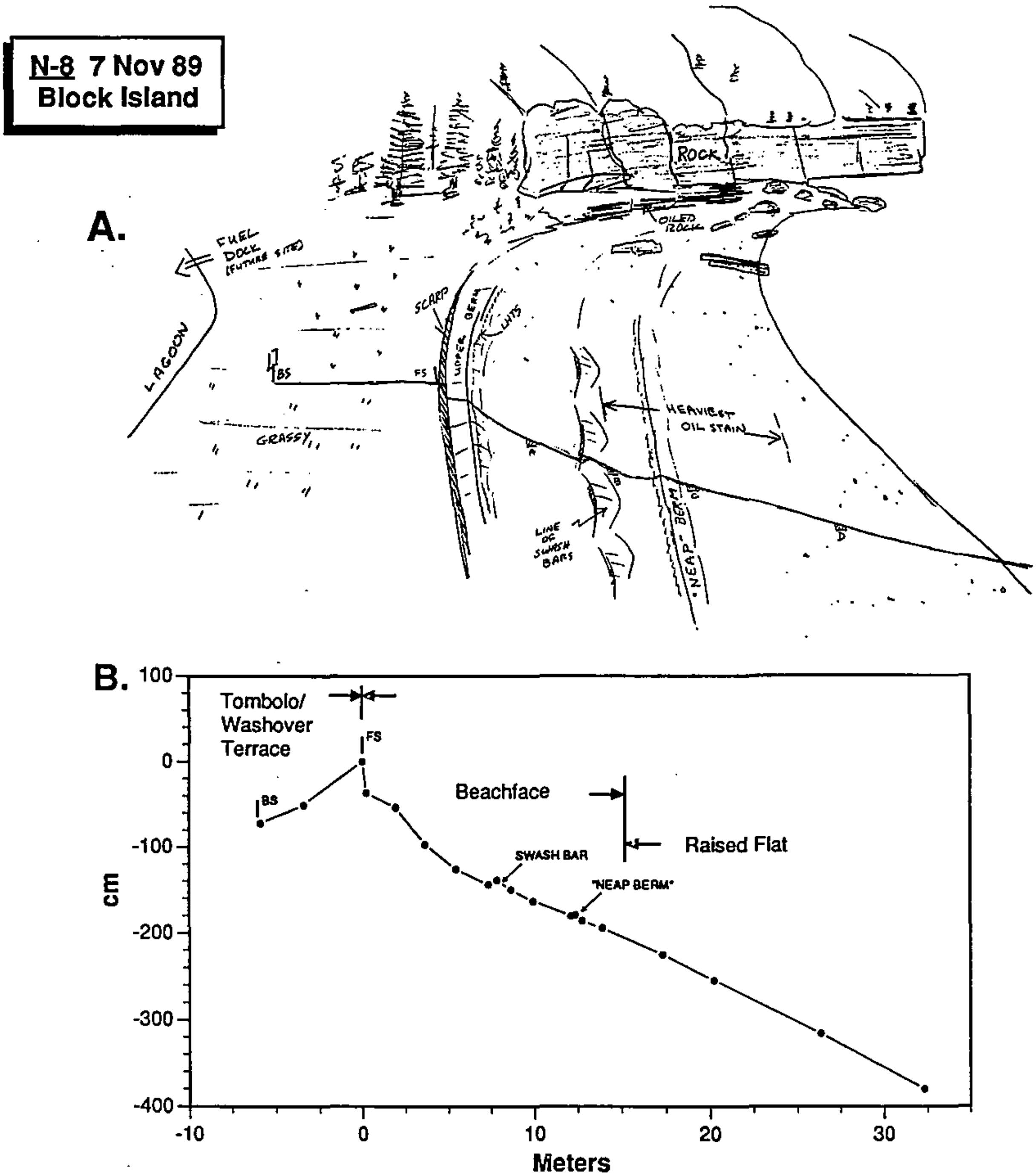


FIGURE 84. Station N-8 on 7 November 1989.

A. Field sketch. Note presence of eroded notch in washover terrace and swash bars and "neap berm" on the beachface. Sediments are coarsest on the lower reaches of the profile. Sketch is a composite by Hayes based on sketches by Michel on 17 September 1989 and Lemon on 7 November 1989.

B. Topographic profile, demonstrating the major morphological components of the station. Note subtle relief of swash bar and "neap berm".

Morphology and Beach Dynamics. The station is composed of three morphological units:

1) Tombolo/Washover terrace

   This surface, which slopes toward the back bay area at an angle of 7°, is highly vegetated with grasses and was strewn with logs and other debris after the high tides of mid-October 1989. A small scarp, averaging 35-40 cm high, was eroded into the face of the terrace during those same high tides. No detailed data were collected on the sediments.

2) Beachface

   This area extends for 15 m seaward from the scarp in the washover terrace. Either spring- and/or neap-tide berms, composed of pebbles or small cobbles, were usually present in this zone. None of the berms exceeded 10 cm in height. The average slope of the beachface was 4-10°.

3) Raised flat

   This zone showed almost no change during the period of study. The coarsest sediments on the beach occurred here, with angular and poorly sorted cobbles being quite common. The subsurface sediments consisted of a hard-packed mixtures of silt, sand, shells, granules, and pebbles.

The profile at station N-8 was surveyed seven times during the course of the study. All of the surveys appear to be quite accurate, but the back stake was removed twice, finally disappearing completely after the 4 March 1990 survey due to construction of the fuel depot. Despite these problems, the dynamics of this beach can be readily understood by a study of the overlay plots in Figure 85. The major event that took place between the 17 September 1989 and 7 November 1989 surveys was the overtopping of the washover terrace during the high tides of mid-October. Sometime during that episode, a notch 35-40 cm high was carved into the seaward side of the terrace. The surface of the beach face was very complex on 7 November 1989. A line of what Gibeaut called "small swash bars" in the field notes, which were composed of large pebbles, occurred about 8 m seaward of the high-tide scarp. Also, a feature he termed a "neap berm", which appeared quite linear in the field sketch and was composed of "large pebbles and small cobbles", occurred 13 m from the scarp. Neither of these features exceeded 5 cm in height. As seen in Figure 85B, the swash bars apparently moved a few meters landward by 4 December 1989. Little change was obvious from any of the subsequent profiles (Fig. 85C). It is clear then, that the fine-grained components of the gravel on this beach are highly mobile on the beachface portion of the profile. However, there is no evidence that a sediment envelope thicker than 10 cm would develop on this beach under normal wave conditions.

Sediments. The sediments of the beach and washover terrace were derived from erosion of the adjacent rocky headlands, which are composed mostly of basaltic lava flows and mafic intrusives (Moffit, 1954). Sediments ranged in size from sand to small boulders, with pebbles being the most abundant type. Because of the short transport distance and low wave energy, the pebbles and large clasts are angular. The percent of cobbles increases towards each headland and the toe of the raised flat, although sand and granules always predominate on the flat. Detailed grain size studies were not done at this site, but there are general sedimentological descriptions available from the trenches dug for sample collection. The beachface sediments were uniform with depth, being composed mostly of pebbles and granules. Occasionally a layer of "peat" or organic rich sediment was observed, but it was not continuous. The raised flat sediments were very different, being dominated by sand and granules, with a minor amount of shell fragments.

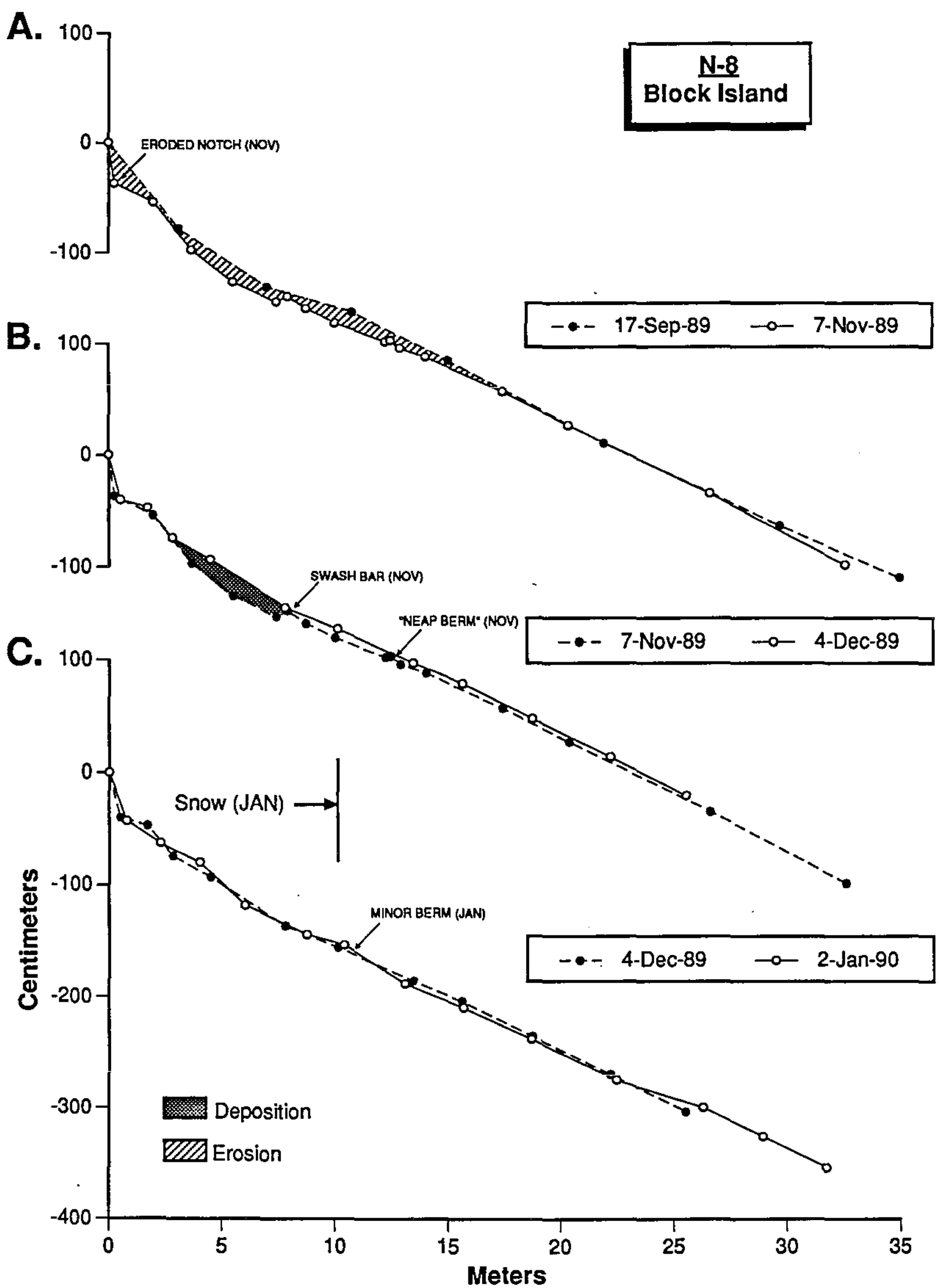
Angular cobbles covered no more than 50 percent of the surface, so there was no armor. The sediments in the bottom of the pits, at about 30 cm, was described as being well consolidated. All of these features characterize this component of the shoreline as a raised seafloor flat.

FIGURE 85. (Facing Page) Profile overlays of station N-8.

A. (17 September 1989 and 7 November 1989) A notch was eroded in the washover terrace during the high spring tides in mid-October.

B. (7 November 1989 and 4 December 1989) The swash bars present in November apparently moved further up the beach and filled in a previous topographic low.

C. (4 December 1989 and 2 January 1990) A minor berm formed in front of the snow line. Otherwise, no change at all.


A.
B.
C.
N-8
Block Island
ERODED NOTCH (NOV)
17-Sep-89
7-Nov-89
SWASH BAR (NOV)
"NEAP BERM" (NOV)
7-Nov-89
4-Dec-89
Snow (JAN)
MINOR BERM (JAN)
4-Dec-89
2-Jan-90
Deposition
Erosion
Centimeters
Meters

It was obvious that this area is an accumulation zone for flotsom. Large accumulations of kelp and algal wrack were always found at the base of the scarp. Numerous logs covered the washover terrace. After the mid-October high tides and storm, the raised flat was covered with a thick mat of seagrasses and Fucus and a large number of logs were floating just offshore.

Oil Distribution Patterns. Surface oil distribution at this station varied widely during the survey (Fig. 86). The surface sediments appeared clean on 7 September 1989, but on 17 October 1989 the entire shoreline was covered 100 percent with a thin oil film. On 7 November 1989, there was 10-30 percent coverage with a light stain on the entire intertidal zone, but by 4 December 1989, the oiling had increased to 20-90 percent coverage with a sticky, thin film. Oil coverage in 1990 went from a very light stain, with less than 5 percent coverage on 5 January, to 10-15 percent covering on 31 January, and 5-20 percent coverage on 3 March. Much of the surface oil occurred as a thin film on the fine sediments and a darker stain or coating on the cobbles and boulders, particularly the underside. Obviously, this beach was a temporary accumulation zone for oil which had been eroded from adjacent and upcurrent sources, just as it is for flotsom.

The surface sediment TPH analyses were surprisingly consistent (Table 14). Except for a 3 March 1990 sample, values ranged from 140-1,000 ppm, and averaged 370 ppm. In general, oil levels in surface sediments steadily decreased by 50 percent, from 17 September 1989 to 3 March 1990. The March sample, with 23,740 ppm TPH, is not described as being unique in the field notes and we have no explanation for it, other than perhaps it contained pebbles with heavy oil on the underside. Because this area tends to accumulate debris, it is likely to continue to be reoiled as long as oil is being mobilized from other shorelines.

It should be noted that the subsurface sediment chemistry data in Table 14 is divided at a sampling depth of 15 cm rather than 25 cm. In the subsurface, a buried layer of oil 5 cm thick was found at depths of 15 to 20 cm throughout the entire intertidal zone (Fig. 88; next color plate). When the layer was sampled, it was shown to contain 10,530-20,640 ppm TPH (Table 14), and it did not change in depth over time. There was too much sampling variation to determine if the oil concentration of this layer changed over time. Above the oiled layer, the sediments from 0 to 15 cm deep had moderate TPH concentrations in September and October, from 150 to 3,790 ppm, with the most oil contamination in the lower half of the shoreline. In September 1989, a soupy mousse seeped into the lowest trench at the raised flat at depths of 10-30 cm and readily sheened. In March 1990, this lower flat still generated sheens when disturbed.

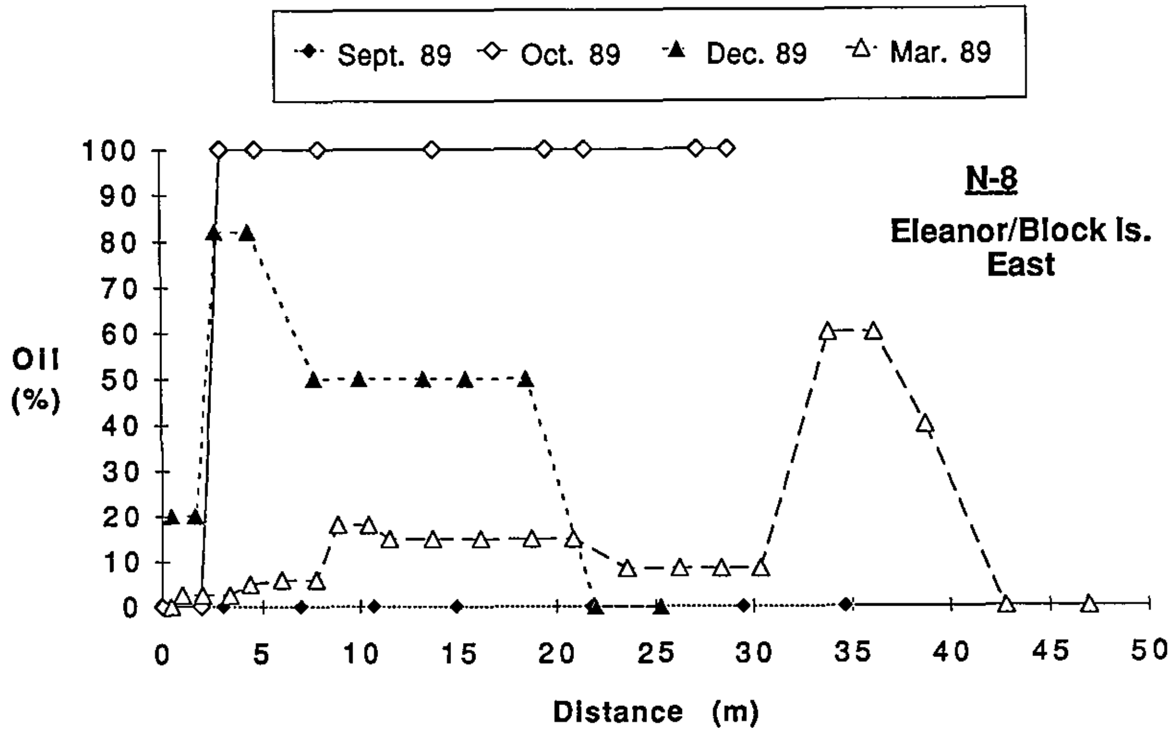


FIGURE 86. Surface oil at station N-8 on Block Island. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months. This station tended to accumulate flotsom and oil sheens from upcurrent areas, so the surface of oil coverage varied widely.

Below the oiled layer, there was little oil. A sample collected in November from the upper beachface at 38-50 depth had <10 ppm TPH. Another sample collected just below the oiled layer (which contained 19,040 ppm) only had 30 ppm.

The buried oil layer probably represents the deeper part of an entire oiled zone which initially extended to the surface. This beach was completely covered with a thick mousse during the spill. The mousse penetrated into the beach, almost saturating the fine sediments with oil. Shoreline treatment activities during the 1989 summer removed oil from the upper 15-20 cm only, leaving the deeper part of the oiled zone intact. Since only the top 5-10 cm of sediment move around, the oiled layer was not mobilized during the storm season. Only when a large storm with a strong south wind occurs, will the sediments be mobilized down to the oiled layer.

TABLE 14. Sediment TPH (in ppm) for N-8 on Block Island by morphological zone.

Surface Samples

Date	Upper Beachface	Middle Beachface	Raised Flat	Mean
9/89		390		390
10/89	310	1,000		660
11/89	540			540
12/89	560			
1/90		220	150	190
2/90	200	230		220
3/90	320	360/23,740	140	270

Subsurface Samples

	Upper Beachface		Middle Beachface		Raised Flat	
Date	< 15 cm	> 15 cm	< 15 cm	> 15 cm	< 15 cm	> 15 cm
9/89	150/920		1,700	20,640	720/1,370	
10/89		16,400	3,790			
11/89		2,010	19,040	30	2,980	
12/89	310			4,460/19,240		
1/90	290	10,530	110	14,940		
2/90	250	20,410				
3/90		850		12,000/17,260	350	

Station N-9

Introduction. Located on a roughly north-south facing shore of Block Island, this station is basically a raised tidal flat surrounded by major rock outcrops with a simple pebble/granule/sand berm on its landward side. The profile is long and flat, extending nearly 100 m on low spring tides. It is one of the very few wide tidal flats in PWS. The shore faces directly across the channel of Upper Passage, a distance of around 1 km. Rock outcrops are present several meters to either side of the profile, and the surface sediments coarsen to cobbles and boulders near both outcrops. The outcrop to the east had a small gravel tombolo behind it where an asphalt pavement formed. There is an open fetch distance of 17 km in a northwesterly direction (45 ° angle to shoreline), but waves generated by winds blowing along that fetch would have to pass 3.5 km down the one-km wide Upper Passage, as well as over and around numerous rock outcrops, before reaching this beach. The area was uplifted around 1.2 m during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the profile on 23 June 1990 are given in Figure 87 and an aerial view of the station is given in Figure 89.

This shoreline segment was heavily oiled and was treated with warm- and hot-water flushing and Inipol in 1989. Although no field observations were made during treatment, this area, with its wide tidal flat surrounded by rocky outcrops, must have caused the cleanup crews many problems. In 1990, an asphalt pavement located south of the station was manually removed and the remaining oil was treated with Inipol. As far as we know, no treatment was conducted along the profile in 1990.

Morphology and Beach Dynamics. This station is divided into four morphological units:

1) Beachface

   This zone is a simple single berm at the spring/storm berm level. The upper beachface is covered with over 70 percent sand and granule, but the lower beachface, which slopes offshore at an angle of 7°, contains abundant pebbles and cobbles.

2) Upper flat

   This rather flat surface, which slopes offshore at 2°, has a cover of more than 60 percent pebbles on the average. A layer of peat underlies the oil-bearing surface sediments at depths of 10 cm or so. Throughout the survey period, a litter of clam shells was scattered over the surface.

3) Lower flat

The surface of this unit is virtually horizontal (Fig. 87B). It also has a predominantly pebble surface, mixed with scattered cobbles, boulders, and broken clam shells. The subsurface peat layer continues under this part of the profile, as well. Ground water drainage rills are common over the upper third of the flat.

4) Bedrock

Several major outcrops are clustered around the bottom of the profile, which was run over a 40 cm high notch in the bedrock ledge (Fig. 87A, B). The rock has an abundant cover of biota, including mussels (Mytilus edulis), barnacles, Fucus, and several additional species of algae. The extreme end of the profile passes over a sediment deposit populated by a dense growth of eelgrass.

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

Sediments. The sediments at this station are derived from erosion of the local bedrock outcrops and soil horizons. The bedrock is composed mostly of metamorphosed basaltic lavas and intrusive mafics (Moffit, 1954). The distribution of surface sediments along the profile on 22 June 1990, illustrated in Figure 87C, was as follows:

1) The upper beachface was covered by over 70 percent sand and granule.
2) The lower beachface and landward part of the upper flat had the highest percentage of cobbles and boulders (20-30 percent) of any part of the profile.

N-9 22 June 90
Block Island

A.

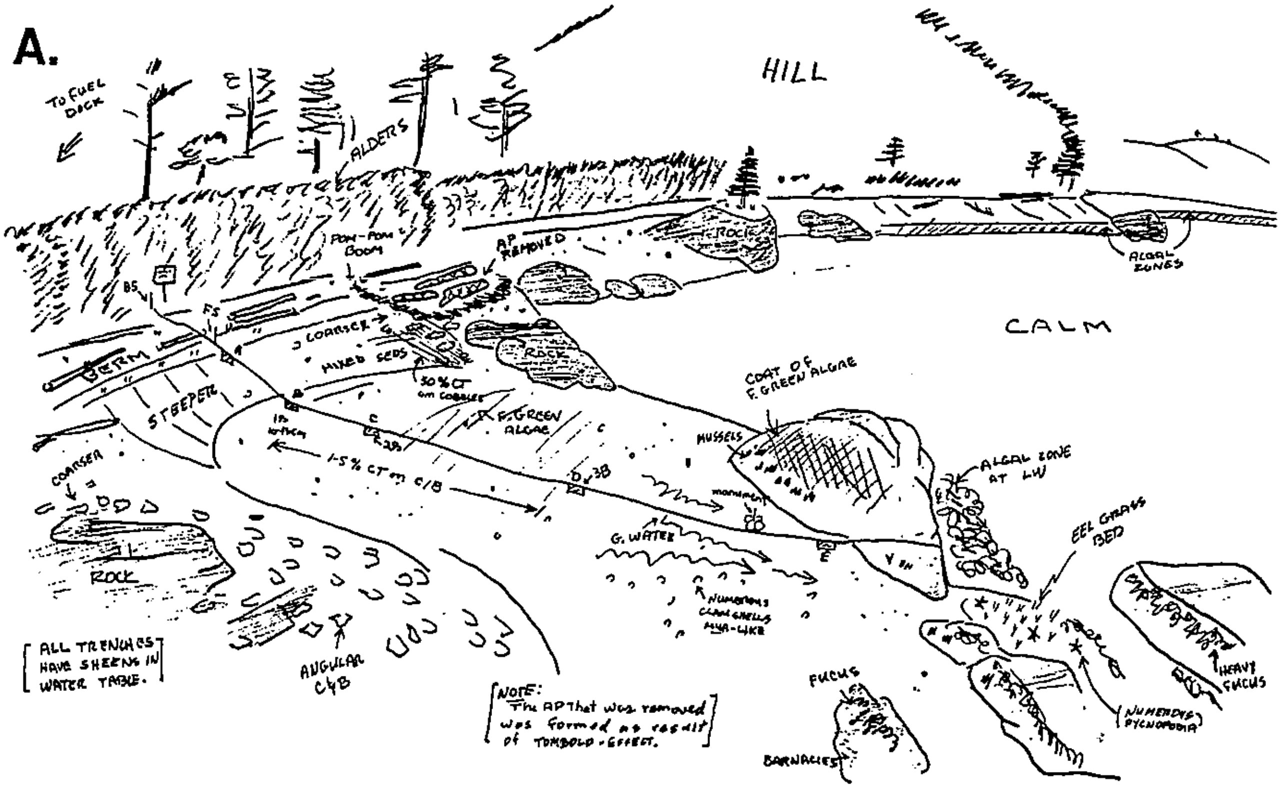


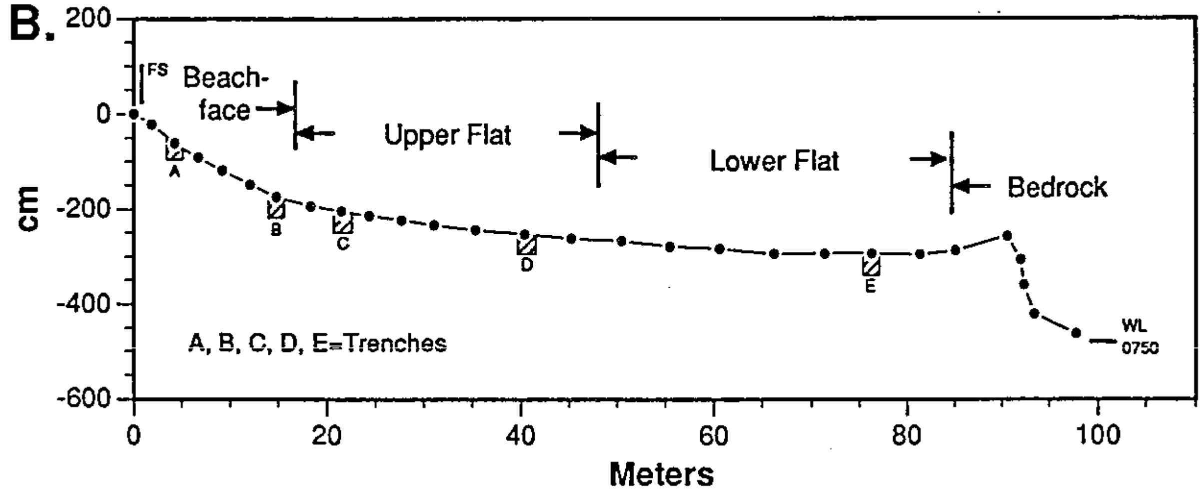
FIGURE 87. Station N-9 on 23 June 1990.

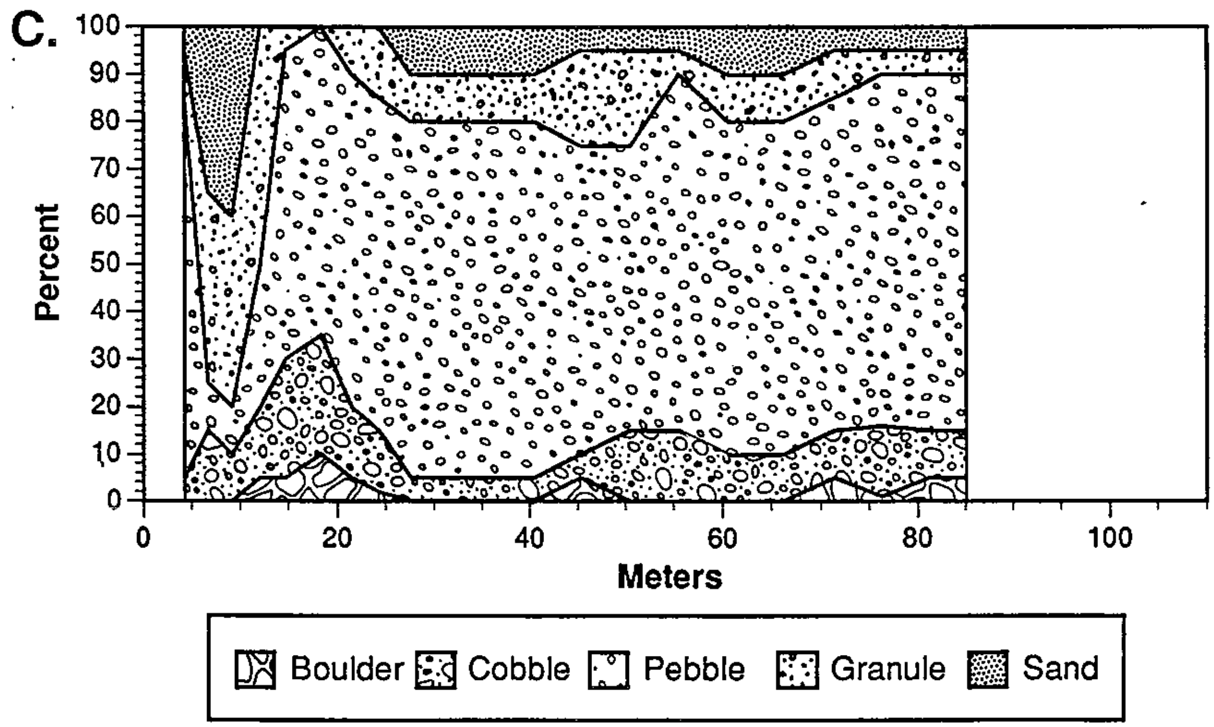
A. Field sketch. The raised tidal flat is surrounded by rock outcrops from which angular cobbles and boulders are derived. The asphalt pavement that had been recently removed from the high-tide area to the south of the profile was formed there as a result of the tombolo effect.

B. Topographic profile, demonstrating the exceptionally flat surface of the raised tidal flat. Four of the five trenches contained peat deposits.

C. Surface sediment distribution pattern based on estimates at 20 of the survey points (circles on diagram B). Note abundance of sand and granule on the upper beachface, increase in cobbles and boulders near the contact between the beachface and upper flat, and predominance of pebbles throughout the rest of the profile.

N-9 22 June 90
Block Island





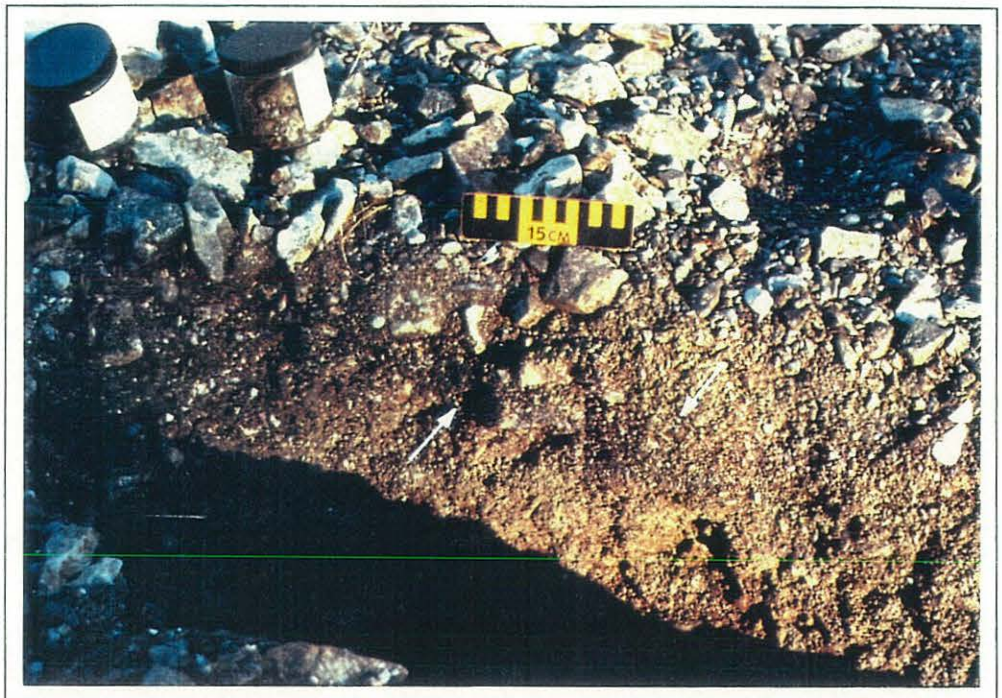


FIGURE 88. Oil layer (arrows) in trench at 20 m mark on profile N-8 on 7 November 1989. This persistent oil layer remained until March 1990, after which the station was abandoned. Photo by D. Hall.

FIGURE 89. Near vertical aerial view of upper part of profile N-9 on 22 October 1989. Profile was run down middle of swale, as indicated by the line. Photo by D. Hall.

3) The rest of the profile was rather uniform, containing roughly 10 percent sand, 10 percent granules, 10 percent cobbles, 5 percent boulders, and 65 percent pebbles throughout.

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

Oil Distribution Patterns. Very little surface oil was observed along any part of this profile during the surveys (Fig. 90A), despite the fact that it was initially heavily oiled. In fact, in September 1989, the entire beach and flat looked clean, although sediment samples of the top 5 cm contained 210-220 ppm TPH (Table 15). In October, the cobbles on the beachface and upper flat had 50 percent coverage by an oil stain and those on the lower flat had a thick coating of oil on the undersides. This beach was obviously reoiled during the October high-tides, and it continued to receive spotty deposits of oil throughout the fall and winter. As a result, the surface sediment chemistry analyses vary widely. March 1990 is an extreme example where scattered mousse patties on the low tidal flat were sampled and contained over 20,000 ppm.

Low levels of oil were detected in surface samples from the beachface, where those samples average 100 ppm. Some oil was measured in the subsurface sediments at depths of 15 to 20 cm, ranging from 10 to 280 ppm. The tidal flat, however, contained somewhat higher levels, ranging from 10 to 680 ppm, with the highest values measured in samples collected on 6 September 1990. Results varied by at least an order of magnitude, and there were no temporal or spatial trends. Sheens formed on the water table in every trench dug in the tidal flat during the surveys, except those on 17 September and 7 November 1989. Sometimes brown oil droplets would also accumulate over time on the water table. Twelve subsurface samples, usually from 5 to 15 cm deep, averaged 240 ppm TPH. The oil did not penetrate any of the peat. At most spills, tidal flats do not remain oiled for long because the water-saturated nature of the sediments limits oil penetration. This flat, however, was raised by the 1964 earthquake and perhaps is more drained than usual. Also, hot-water flushing and other treatment activities surely entrained oil into the sediments. This shoreline segment was intensively washed and there was no way to prevent oiled sediments from being flushed onto the flat. Whatever the mechanism, once contaminated, the oil removal rates for such flats will be slow. Furthermore, there is little that can be done to speed the natural removal process; usually any such attempts only cause more disturbance.

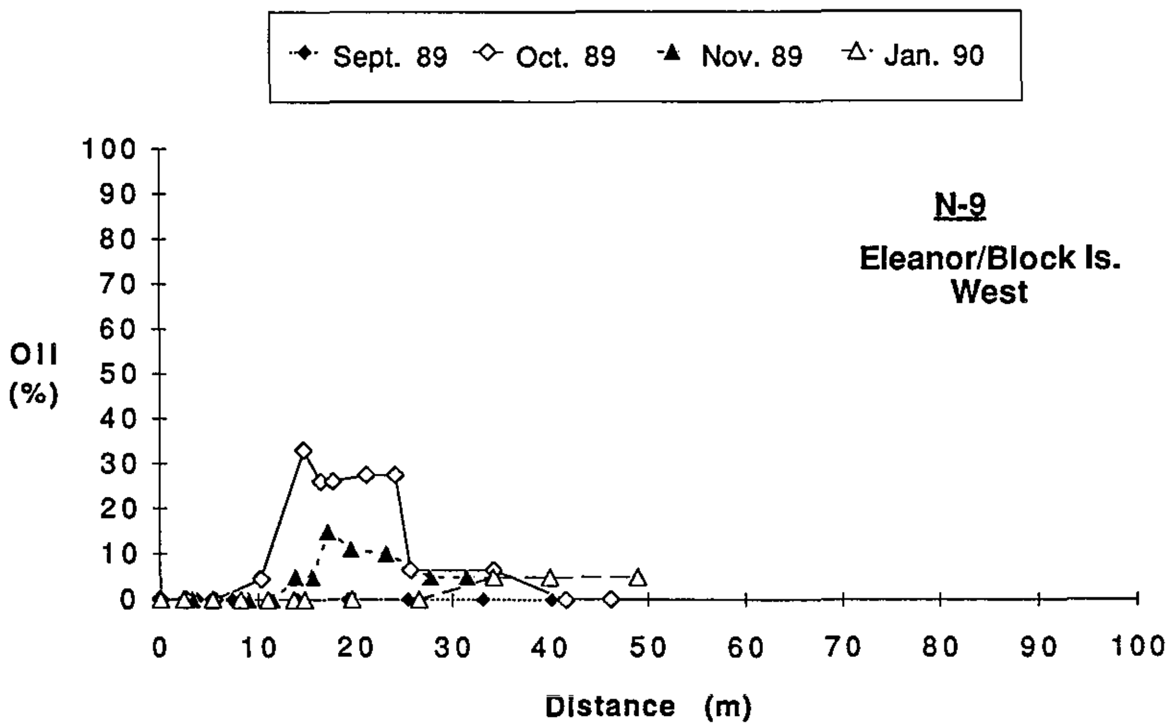


FIGURE 90. Plots of the distribution of surface oil coverage at selected survey periods for station N-9, Block Island. Note that no surface oil was observed in September 1989. The shoreline was re-oiled sometime in October. Only scattered traces of oil were observed on the tidal flats after January.

TABLE 15. Sediment TPH (in ppm) for station N-9 on Block Island by morphological zone.

Surface Samples

Date	Beachface	Upper Flat	Lower Flat
9/89	210	220	
10/89		200/340	260
11/89	50	30	450
1/90	70		60/140/17,200
2/90			260/600
3/90	60	50	1,120/19,710/21,460

Subsurface Samples

Date	Beachface < 15 cm	Upper Flat < 15 cm	Lower Flat < 5 cm
10/89		10/260	
11/89	10	240	
1/90			40
2/90	280		50/220/420
3/90	80	100	
6/90			<10
9/90		680	620

Station N-11

Introduction. This station is located near the middle of the west side of Crafton Island on the south side of a small, circular indention in the shoreline. The entrance to the indention faces west across 1.5 km of open water to an arm of the mainland of the Kenai Peninsula. The entrance area to the indention has an effective fetch of 23 km to the north-northwest. However, the orthogonals of waves generated by winds from that direction would strike the general shoreline at an angle of 22-23° and would refract into the indention, the entrance to which is partially blocked by a large rock outcrop. Therefore, station N-11 has a relatively low wave-energy setting. Pebbles are the dominant sediment type and subsurface peat deposits give the ground a "spongy" feeling at times.

The profile is located on a short, high-level tombolo that connects two bedrock highs and is backed by an intertidal lagoon. The area was uplifted about 1 m during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the station on 31 May 1990 are given in Figure 91 and two photographs are presented in Figure 92.

The site was moderately to heavily oiled, and any oil that came ashore in this area would have been effectively trapped by the narrow entrance. This segment was approved for hot-water flushing, but at the time cleaning crews started work on this area, the monitors decided to allow only manual removal because of the sensitivity of the site. Bioremediation was conducted twice, with Inipol in 1989 and Customblen only in 1990.

Morphology and Beach Dynamics. The profile at station N-11 can be subdivided conveniently into three morphological units:

1) Upper beach

   This zone, which slopes offshore at 5°, has a thin veneer of angular cobbles, pebbles, and boulders (<10 percent) over bedrock. Some asphalt pavement was still present on 31 May 1990.

2) Lower beach

   Surface sediments are finer on this unit, which is dominated by pebbles. Peat underlies the surface sediments in places. No depositional features were observed on this surface, which slopes offshore at 5°.

3) Tidal flat

This raised tidal flat slopes offshore at a much smaller angle (2°) than the upper two beach units (Fig. 91B). The surface sediments, which are covered by a dense growth of brown algae, are somewhat finer-grained than the rest of the station.

The profile at station N-11 was surveyed seven times during the study. The upper beach was overtopped during the high spring tides of mid-October. Sexton, Gibeaut, and Balcom (1990; p. 57) made the following statement regarding the high tides:

> "Comparison of the plotted profiles in conjunction with field observations indicated that during the large tides in October and November 1989, the top of the beach did erode. This change is most probably attributed to the removal of a large mat of rafted material from the top of the beach."

The textural attributes of the surface sediments on this station, which are somewhat angular, poorly sorted, and well-packed, indicate that sediment motion is limited. There was no evidence from the field data that depositional berms were ever present on the beach. These observations, plus analysis of the sequential profile measurements, lead us to believe that this beach has almost no potential to develop a mobilized sediment envelope.

Sediments. Sediments at this station are no doubt derived from the local bedrock outcrops. The bedrock of the area is primarily interbedded slate and graywacke that is closely folded and schistose in nature, according to Moffit (1954). The distribution plot in Figure 91C shows that the surface sediments of the upper and lower beach are mostly pebbles, with an abundance of cobbles on the upper beach.

N-11 31 May 90
Crafton Island

A.

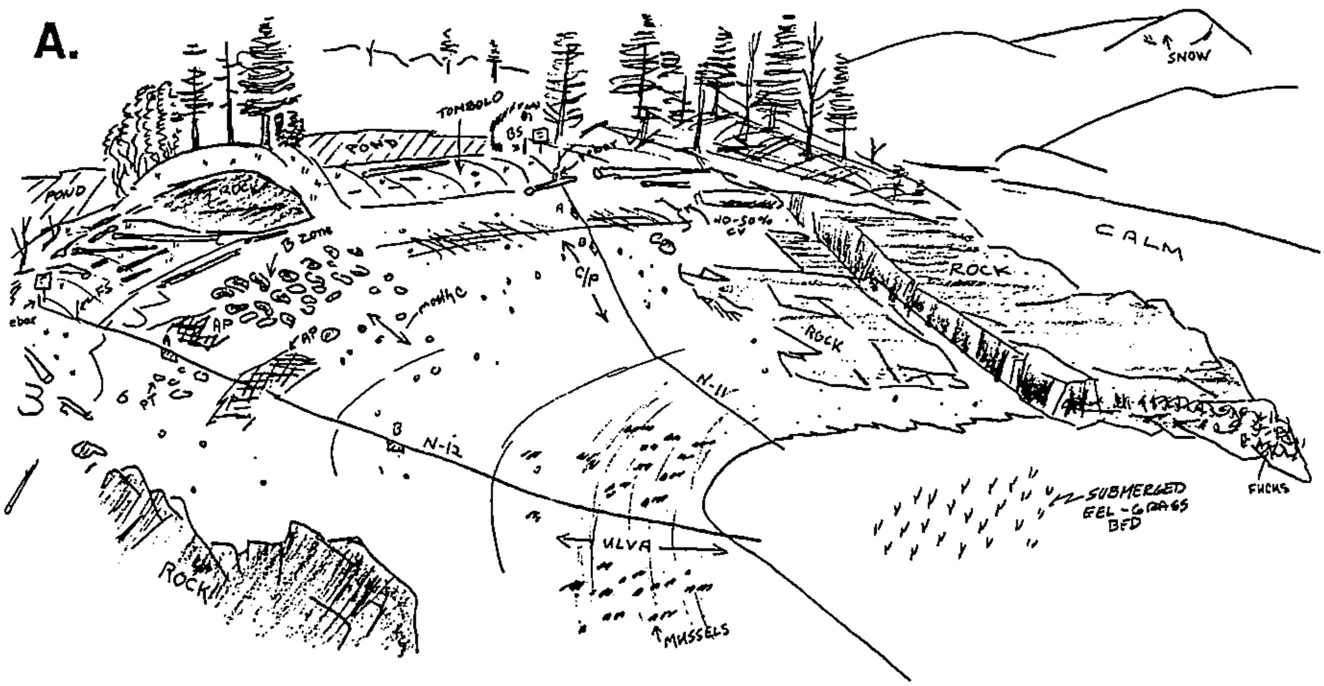
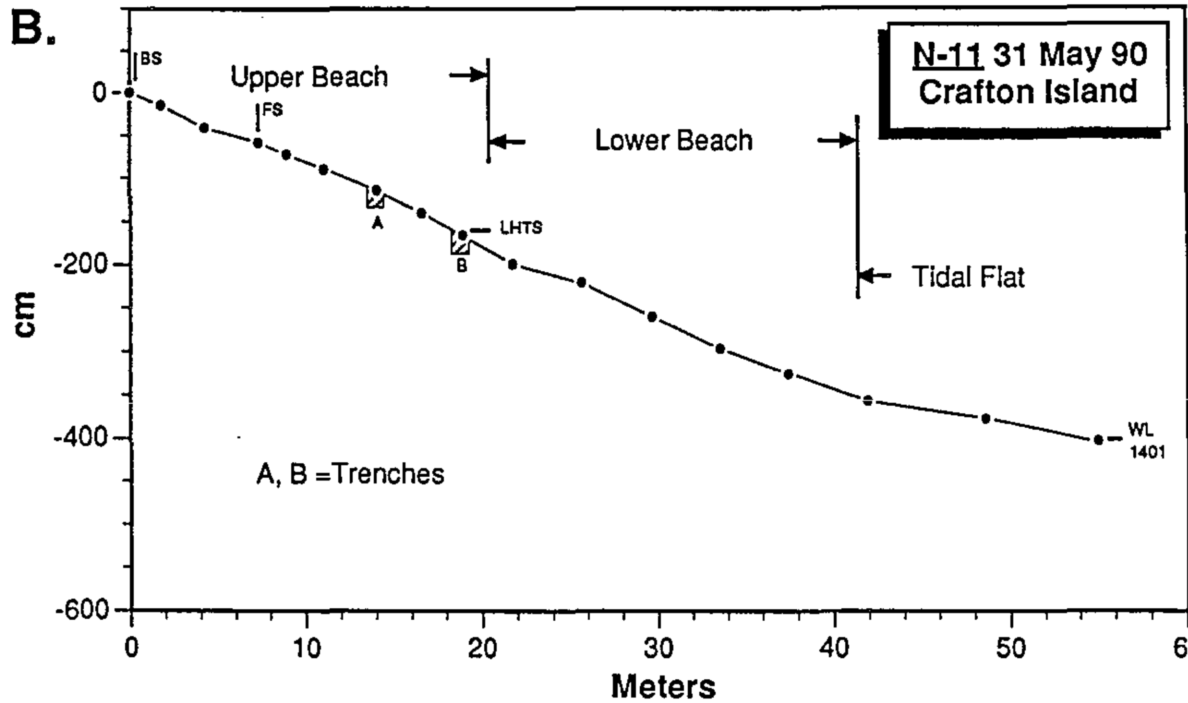


FIGURE 91. Station N-11 on 31 May 1990.

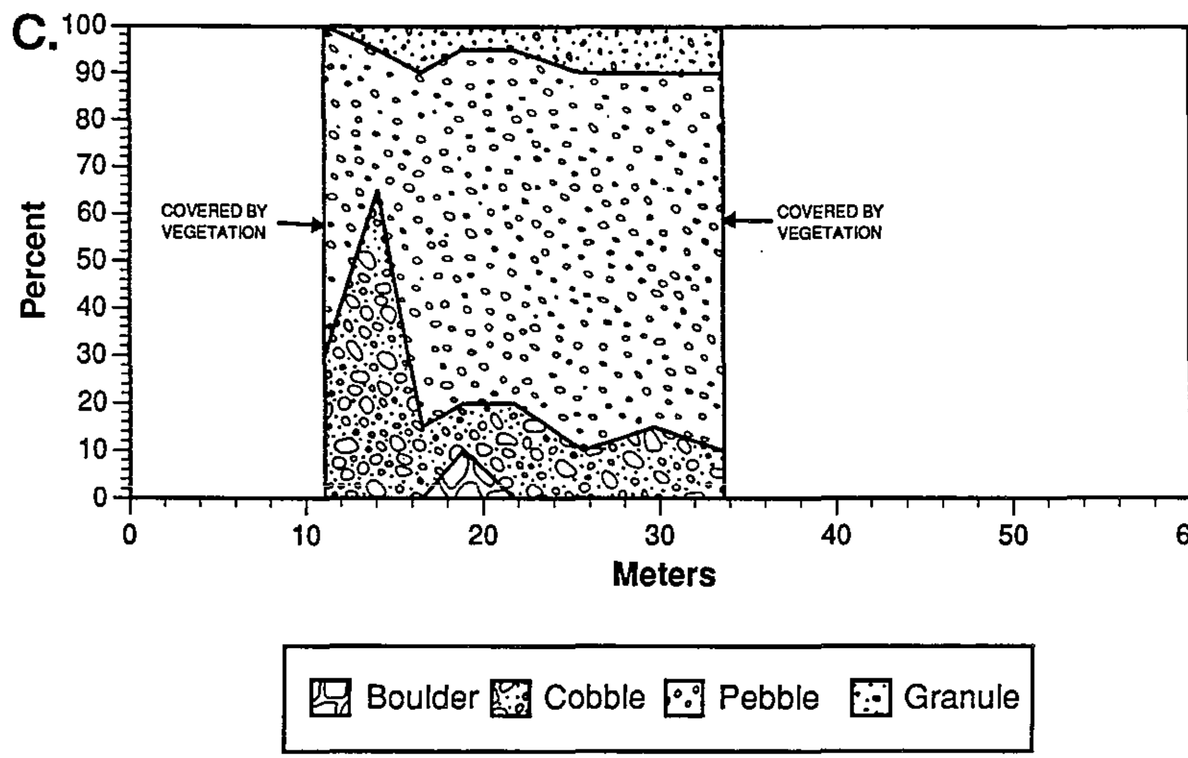
A. Field sketch showing both stations N-11 and N-12. Note distinct break between raised tidal flat and beachface. A well-developed eelgrass bed occurs on the shallow flat just off the profile.

B. Topographic profile, which illustrates the slope differences among the three primary subdivisions of the station.

C. Surface sediment distribution plot based on grain-size estimates of 8 survey points (circles on profile shown in B). Except for the zone of abundant cobbles on the upper beachface, pebbles dominate the upper and lower beach. The tidal flat had a heavy cover of algae when the survey was done.



B.
BS
Upper Beach
FS
Lower Beach
N-11 31 May 90
Crafton Island
A
B
LHTS
Tidal Flat
WL
1401
A, B =Trenches
cm
0
-200
-400
-600
0
10
20
30
40
50
60
Meters



C.
Percent
100
90
80
70
60
50
40
30
20
10
0
COVERED BY VEGETATION
COVERED BY VEGETATION
0
10
20
30
40
50
60
Meters
Boulder
Cobble
Pebble
Granule

A total of 22 trenches were dug on this profile during the study. Peat was encountered about 6 cm under the surface of the lower beach during the 4 September survey. The sediments in the trenches did not show the distinctive armoring that was present on many of the beaches (Fig. 92B), because of the lack of significant wave action at this site. There was always abundant groundwater drainage out of the lower beach, due perhaps to the presence of the peat, which forced the water to flow laterally and out of the overlying beach sediments.

Oil Distribution Patterns. The distribution of oil at this site was difficult to assess. The sediments were dark and organic rich. The water table was very high and trenches rapidly filled with water. Heavy vegetation covered the upper and lower section of the intertidal zone. Figure 93 shows the distribution of surface oil as estimated visually. On 18 September 1989, black oil covered the first 10 m; the oil on the remainder of the profile occurred as a thin to very thin film, consisting mostly of sheens generated by groundwater discharge from the upper beach. The 5 m band of black oil persisted throughout the study, even until the 4 September 1990 survey. This oil band is also reflected in the surface sediment analyses, shown in Table 16 (see also trench photo in Fig. 92B). Even in 1990, TPH levels were between 10,000 and 20,000 ppm. There were patches of oil on the lower beachface; note that the TPH levels bounce around from 30 to 11,750 ppm. The sketch sheets commonly showed bands of scattered oil patches. As would be expected, there has been little change in the degree of surface oil contamination over time. Visually, the site looks cleaner, but the high variability in oil distribution makes it impossible to demonstrate a decrease with sediment analysis. There has been minimal contamination of the lower tidal flat, which is fringed by a lush eelgrass bed. Even though the site was not hot-water washed, sheens have contaminated the surface sediments with 80-90 ppm TPH. Two samples from this zone contained less than 100 ppm TPH. It should be noted that the high natural organics in the sediments could raise the background level of the TPH analysis somewhat.

Because of the low permeability of the sediments, little penetration of oil into the substrate is expected, and the results in Table 16 confirm this. Only the upper beach, which is dominated by pebbles even with depth, showed any oil with depth. On 18 September 1989, oil was reported to extend to 50 cm and the samples in Table 16, which had 340 and 560 ppm oil, were collected from two separate trenches at 30 and 50 cm depths. Black oil was always observed in trenches in this zone of subsurface oil contamination, which extends for about a 5 m width across the beach.

During the 4 September 1990 survey, Customblen granules were seen below the surface cobble layer. Oil on the top of the cobbles had started to weather to a dry stain, but the oil at depth was still quite fresh and readily sheened (Fig. 92B).

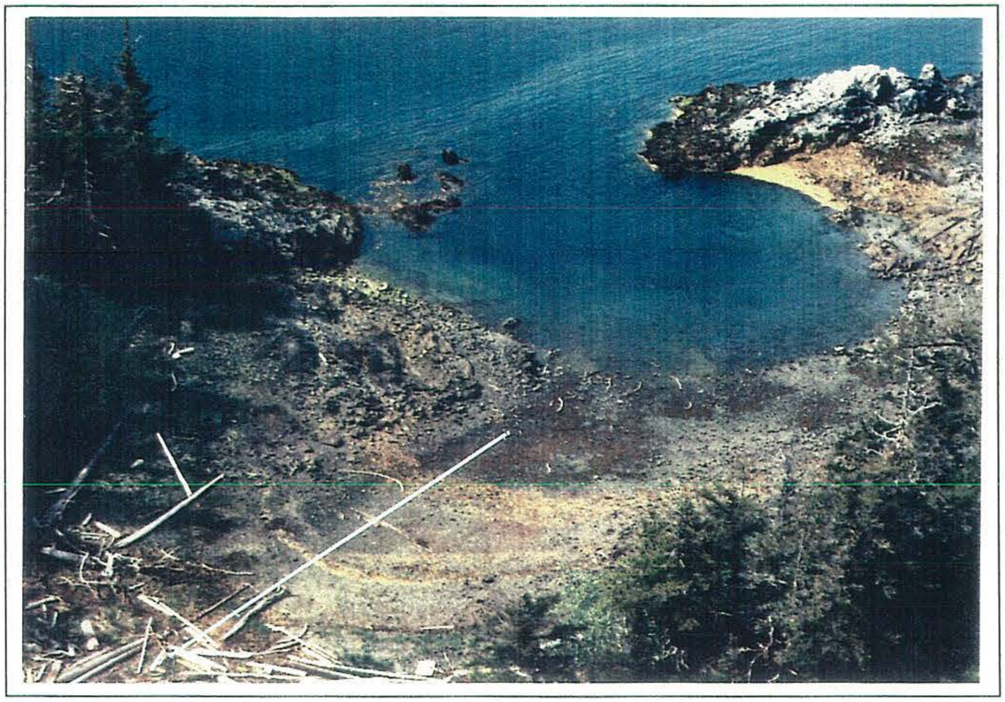
Little to no oil was found in the subsurface on the lower beach or tidal flat. The high water table and constant discharge of groundwater has prevented significant penetration. Only one sample collected from the lower beach substrate showed high oil levels. This sample (containing 1,910 ppm TPH) was collected from a greasy zone 1-5 cm below the surface, which was perched on top of a peat layer that extended down at least to 24 cm. The peat was clean. All of the samples from the tidal flat were collected at 10-15 cm depth, and two samples had more than 100 pm TPH—sometimes higher than the surface sample from the same zone. It is uncertain what this deeper contamination is related to, since washing was not used. There could have been disruption of the sediments by trampling or reworking of oiled surface sediments by benthic organisms.

FIGURE 92. (Facing Page) Photographs of station N-11.

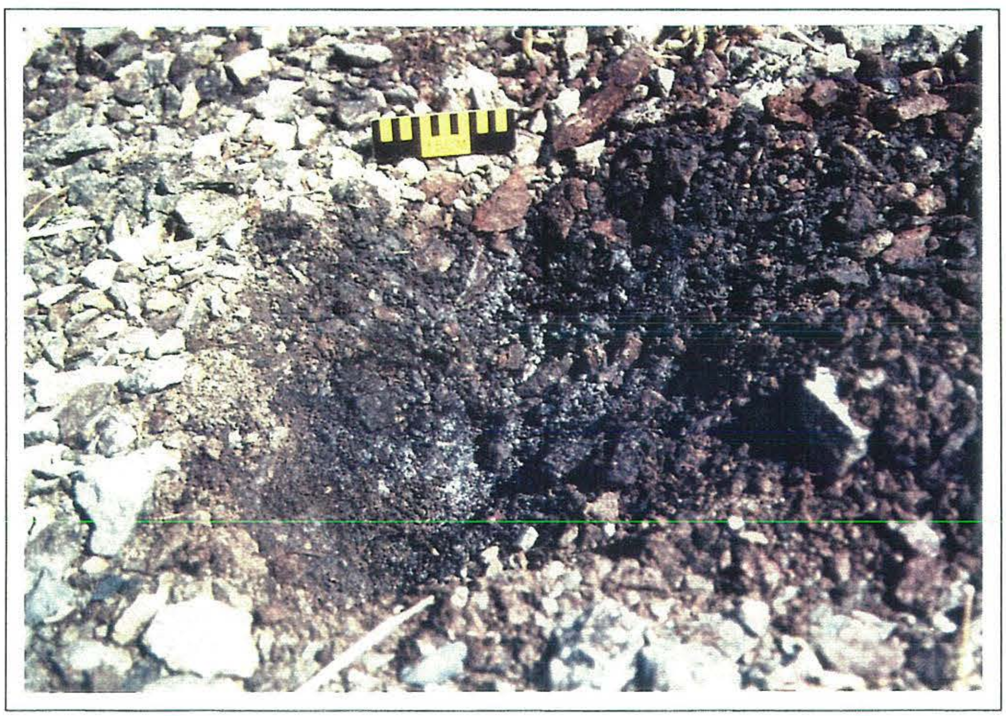
A. Oblique aerial view at low-tide on 31 May 1990. Profile line is indicated. The large rocks in the upper right shield the station from waves approaching from the north. Photo by M. Hayes.

B. Trench B on 31 May 1990 (see profile in Fig. 91B for location). Note shallow oil on impermeable substrate. Photo by D. Noe.

A.



B.



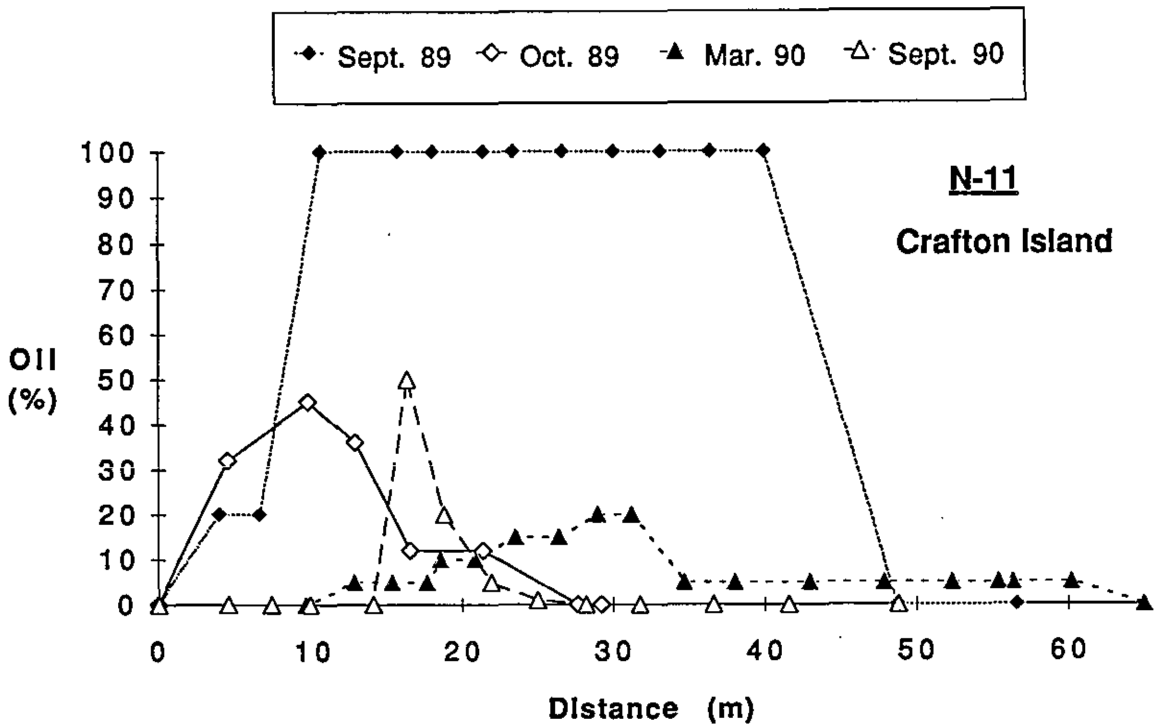


FIGURE 93. Plot of the distribution of surface oil at N-11 on Crafton Island for selected surveys. There is a persistent band of heavy oil on the upper beach. In September 1989, the rest of the shoreline was covered by a thin sheen.

Observations on Biota. There are NOAA biological monitoring quadrats at three elevations in this area. The low quadrats are located on the N-11 profile line, on the tidal flat almost at the water line (Fig. 91). The sediments in this zone did not appear to be very disturbed. However, during low tide, groundwater containing oil sheens drains across this zone. Heavy accumulations of wrack can cover this entire area at low tide, perhaps trapping the oil onto the vegetation. This zone is very different from the mid quadrats, which are located on the N-12 profile just below the position of trench B (Fig. 91A). This side of the pocket beach is rocky, drier (no groundwater rills), and had only trace amounts of visible oil. The upper quadrats were located on the N-12 profile, just below the broken asphalt pavement (shown as AP on Fig. 91A). By September 1990, the pavement had been removed (and treated with Inipol).

TABLE 16. Sediment TPH (in ppm) for N-11 on Crafton Island by morphological zones.

Surface Samples

Date	Upper Beach	Lower Beach	Tidal Flat
9/89	1,750/3,080	80	
10/89	80	1,100/2,750	
11/89		1,150/1,680	
1/90	3,080/12,060	170	80
2/90	180	30	
3/90	11,040/20,200	11,750	90
9/90	17,880		

Subsurface Samples

	Upper Beach		Lower Beach		Tidal Flat	
Date	< 25 cm	> 25 cm	< 25 cm	> 25 cm	< 20 cm	> 20 cm
9/89		340/560	40/70		130	
10/89	240		<10			
11/89	50		<10			
1/90	1,050		20		20	
2/90	80		30		110	
3/90			70			
9/90	4,460/1,370		1,910	(greasy zone @ 1-5 cm)		

ROCKY RUBBLE SLOPES WITH RAISED BAY BOTTOMS

General Description of Shoreline Type

Many of the more protected embayments within PWS contain steeply sloping, rocky rubble shorelines that are rarely affected by significant wave action. Because much of PWS was uplifted during the 1964 earthquake and many of these types of shorelines occur in the shallower, upper extremities of the bays, the intertidal zone is an odd combination of steep rubble slopes and attached bay bottoms, which generally have a flatter slope. Three of the NOAA permanent stations are of this type, which we call rocky rubble slopes with raised bay bottoms—station N-5 near the head of Snug Harbor, station N-13 well inside Herring Bay, and station N-12, which is located adjacent to station N-11 on the small embayment on the west coast of Crafton Island.

Station N-5

Introduction. This station is located well inside of Snug Harbor on Knight Island (Fig. 16). On our ESI maps, this shore would be classified as number 8A, sheltered rocky shoreline with loose rubble. The profile begins on a bedrock ledge and passes down over coarse rubble debris on the upper beach to somewhat finer material on the lower beach. Clasts are angular to subangular and poorly sorted. Heavy growth of *Fucus*, barnacles, and mussels occur at the lowest reaches of the profile.

This station is located on a curving shoreline that faces in a SSE direction down Snug Harbor, an effective fetch distance of 1.5 km. In order to reach the study site, waves entering Snug Harbor from the open Sound would have to travel 2 km into the Harbor and then bend at a right angle and travel another 1.5 km to the study site. Needless to say, this is a low-wave-energy beach. This part of Knight Island was uplifted around 2 m during the 1964 earthquake. A field sketch, beach profile, and surface sediment distribution plot for the station on 31 May 1990 is given in Figure 94, and two photographs are given in Figure 95.

The site was moderately oiled. This shoreline is a set-aside for research purposes and has not received any treatment following the spill.

Morphology and Beach Dynamics. The intertidal part of the station, excluding the bedrock outcrop behind the beach, is classified into two units:

1) Rubble slope

This part of the profile is primarily a rubble strewn bedrock surface that slopes steeply offshore (11°). The sediment veneer is usually quite thin. The rubble is mostly boulder-sized blocks that have fallen from the bedrock scarp behind the shore.

2) Raised bay bottom

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

The beach profile at N-5 was surveyed six times during the study (Table 4). There were no significant changes of the topographic surface and no indication of sediment motion during the entire study.

Sediments. The sediments at this station were derived from the local bedrock outcrops. We determined the composition of 60 clasts at the site and found that all but two were greenstone (metamorphosed mafic igneous rocks). The plot of the surface sediment distribution pattern on the profile in Figure 94C shows that grain size decreases significantly in an offshore direction. Boulders, which make up 20-30 percent of the surface sediments of the rubble slope, decrease to less than 10 percent of the total near the bottom of the raised bay bottom. Pebbles increase from 20-30 percent of the sediments on the slope surface to around 50 percent at the base of the raised bay bottom. Cobbles show a uniform distribution throughout the profile.

The texture of the surface sediments were studied in detail at three sites on this profile on 31 May 1990. A plot of (L+I)/2 versus distance along the profile, which is given in Figure 96, clearly demonstrates the coarse-to-fine grain size trend. Estimates of the roundness of the 60 clasts measured yielded an average ρ value of 2.16, or near the border between angular and subangular. The coarse sediments at this site are rarely, if ever, moved by wave action. The scatter plot given in Figure 28 contrasts the low angularity of the clasts at this site with the more rounded clasts at station N-1, an area subject to much greater wave action.

N-5 31 May 90
Snug Harbor

A.

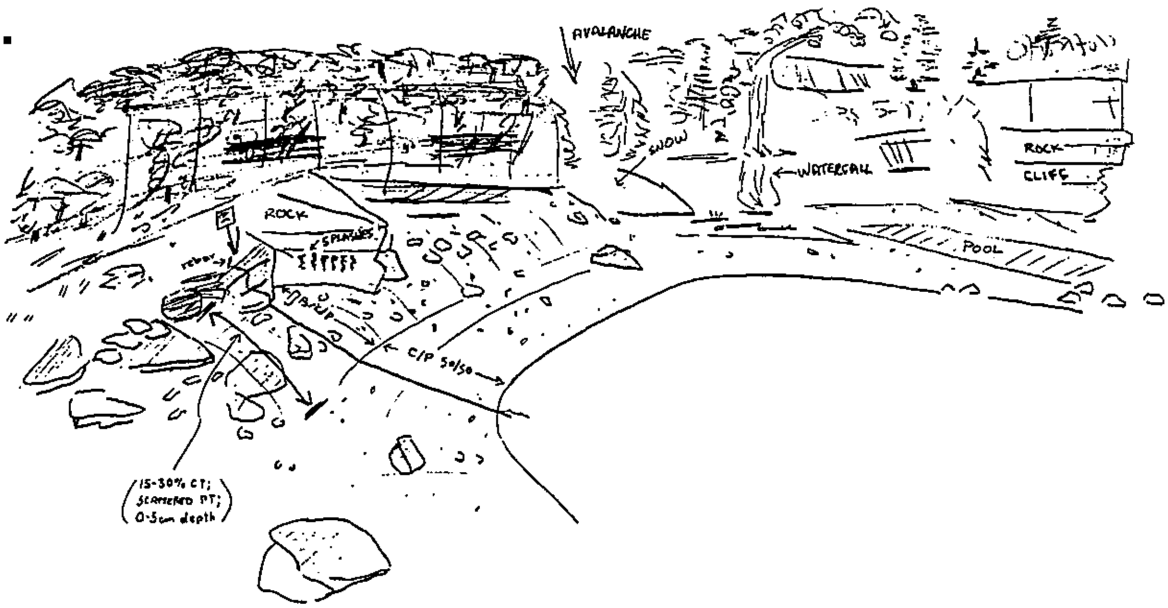


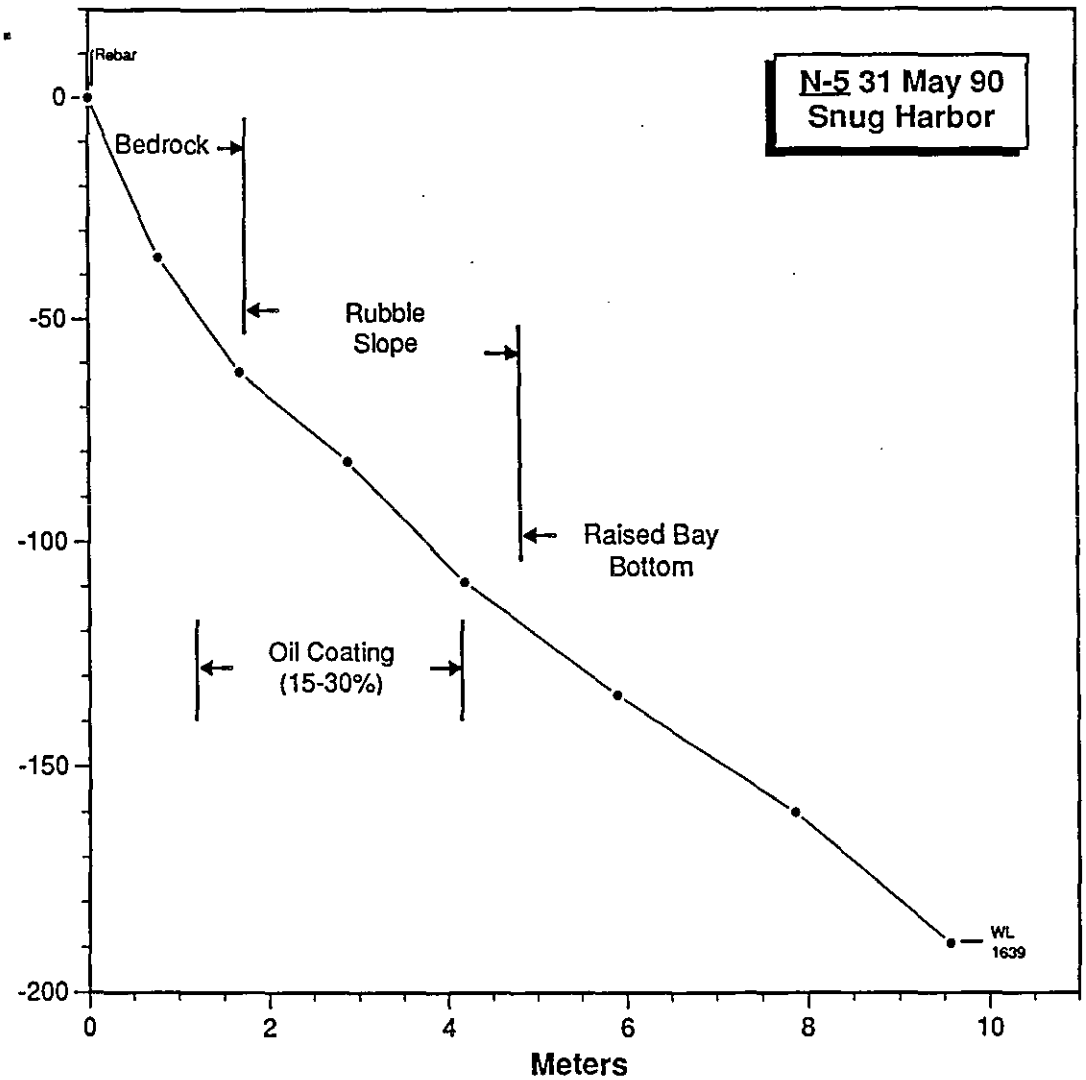
FIGURE 94. Station N-5 on 31 May 1990.

A. Field sketch, illustrating the narrow and steep character of the beach. Note oil splashes on the bedrock. Oil could not penetrate the impermeable substrate of this beach.

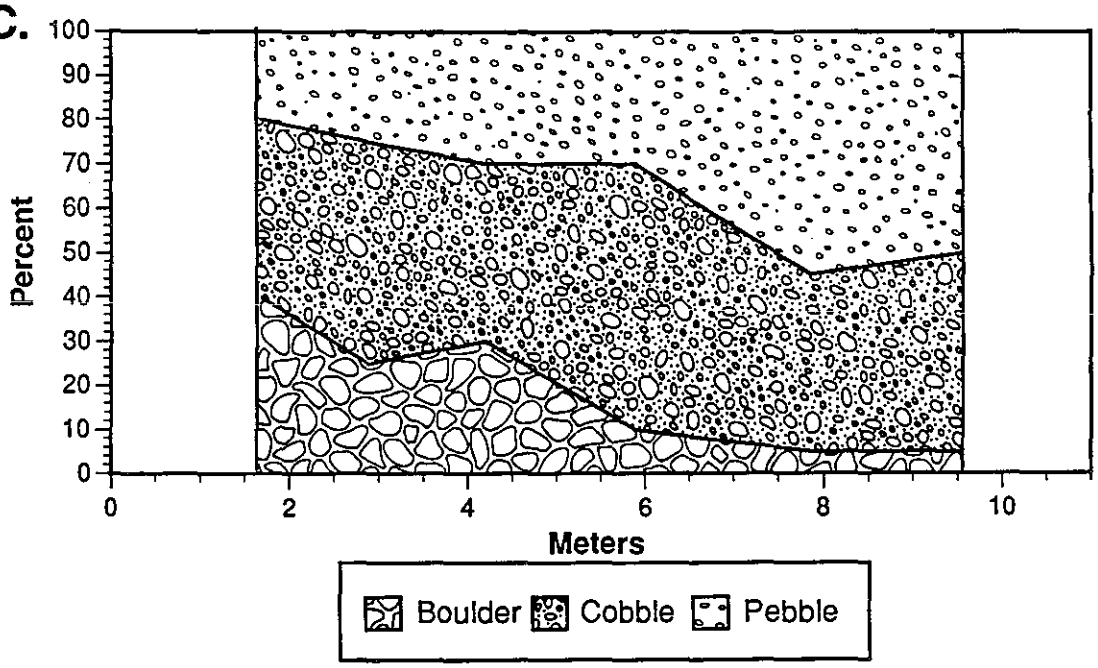
B. Topographic profile. This steep beach is subdivided into a rubble slope, and a somewhat flatter raised bay bottom.

C. Surface sediment distribution plot based on visual estimates at 6 survey sites (circles on plot in B). Note systematic change from coarser to finer material in an offshore direction.

B.


N-5 31 May 90
Snug Harbor
Rebar
Bedrock
Rubble
Slope
Raised Bay
Bottom
Oil Coating
(15-30%)
WL
1639
cm
0
-50
-100
-150
-200
0
2
4
6
8
10
Meters

C.


Percent
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
Meters
Boulder
Cobble
Pebble

A total of 11 trenches were dug on this profile, the deepest reaching 32 cm. The rubble slope overlays a zone of angular pebbles and cobbles supplemented by a matrix of sand and mud. Pebbles, shell hash, sand, and mud were the dominant subsurface sediments of the raised bay bottom. Oil was never found deeper than 2 cm, presumably because of the impermeable nature of the muddy subsurface sediments.

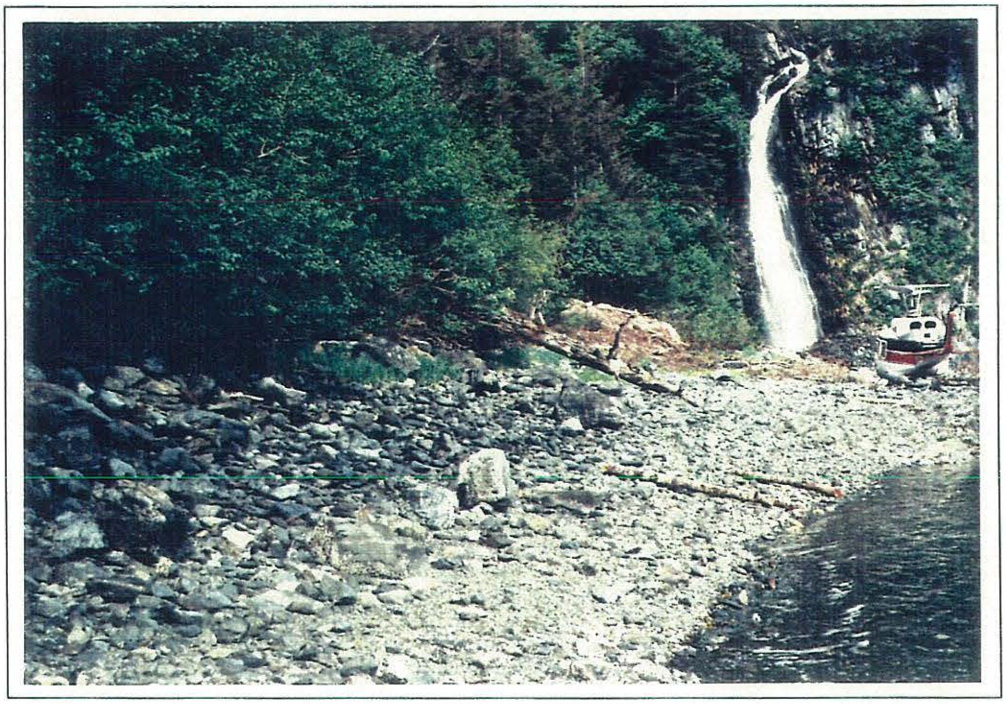
Oil Distribution Patterns. The site was moderately oiled, and no treatment was conducted because it is a set-aside. The surface oil distribution as estimated during selected surveys is shown in Figure 97. At the high-tide line, there was a band of 10 percent coverage of black oil in September 1989, with no apparent oil elsewhere. The December and January observations were nearly identical, showing 10-30 percent oil coverage on the upper part of the raised bay bottom, indicating that re-oiling had occurred. By May, less than 5 percent oil was observed in this zone, mostly as scattered mousse patties. The oil band had weathered to a dull black stain and coat on the rock surface, with 5-20 percent coverage in September 1990.

FIGURE 95. (Facing Page) Photographs of station N-5.

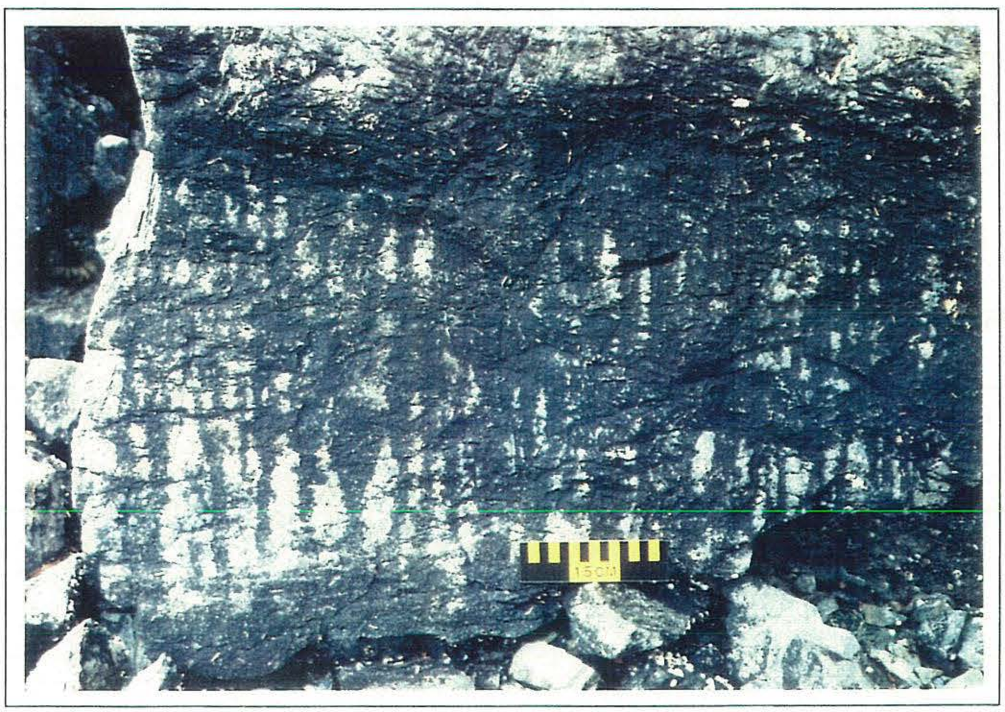
A. View looking east from profile line on 31 May 1990. Note sharp decrease in grain size at the break in slope. Tide was rising rapidly, covering the raised bay bottom. Photo by M. Hayes.

B. Splashes of oil on bedrock above the normal high-tide line. Photo was taken on 31 May 1990 by M. Hayes.

A.



B.



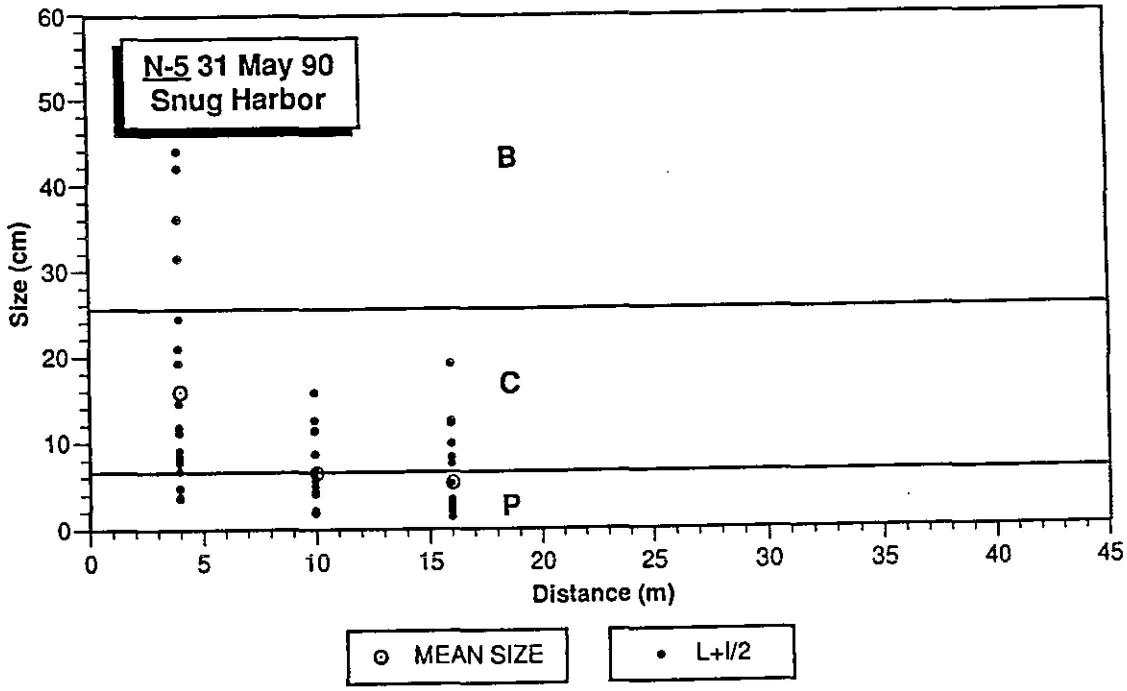


FIGURE 96. Plot of clast size (L+I)/2 versus distance along profile for station N-5 on 31 May 1990. The coarse-to-fine trend in an offshore direction is typical for stations in the class—rubble slopes with raised bay bottoms. Twenty randomly selected clasts were measured at each sampling site.

The results of sediment sample analyses are shown in Table 17 and support the visual observations completely. The rubble slope was heavily oiled but the actual amount of oil varied widely, depending on how the sample was collected. The trend, though, is for lower levels of oil though time. Surface sediments on the raised bay bottom were lightly contaminated, with 100 and 340 ppm TPH for samples collected during the first September 1989 survey, and 30-150 ppm thereafter. Note that this lower zone had only slight subsurface oil contamination, supporting the hypothesis that most subsurface contamination at lower tidal elevations on sheltered shorelines was a result of sediment disturbance during cleanup. There was no deep subsurface oil at this site, even at the heavily oiled upper zone, primarily because the sediment veneer was thin and hard packed. The subsurface samples in Table 17 were collected at depths of 18 to 30 cm, so the sediment layer was at least that thick in places. These results are in contrast with those for station N-13 in Herring Bay (discussed below), which is a similar shoreline type and a set-aside that has oil at depth.

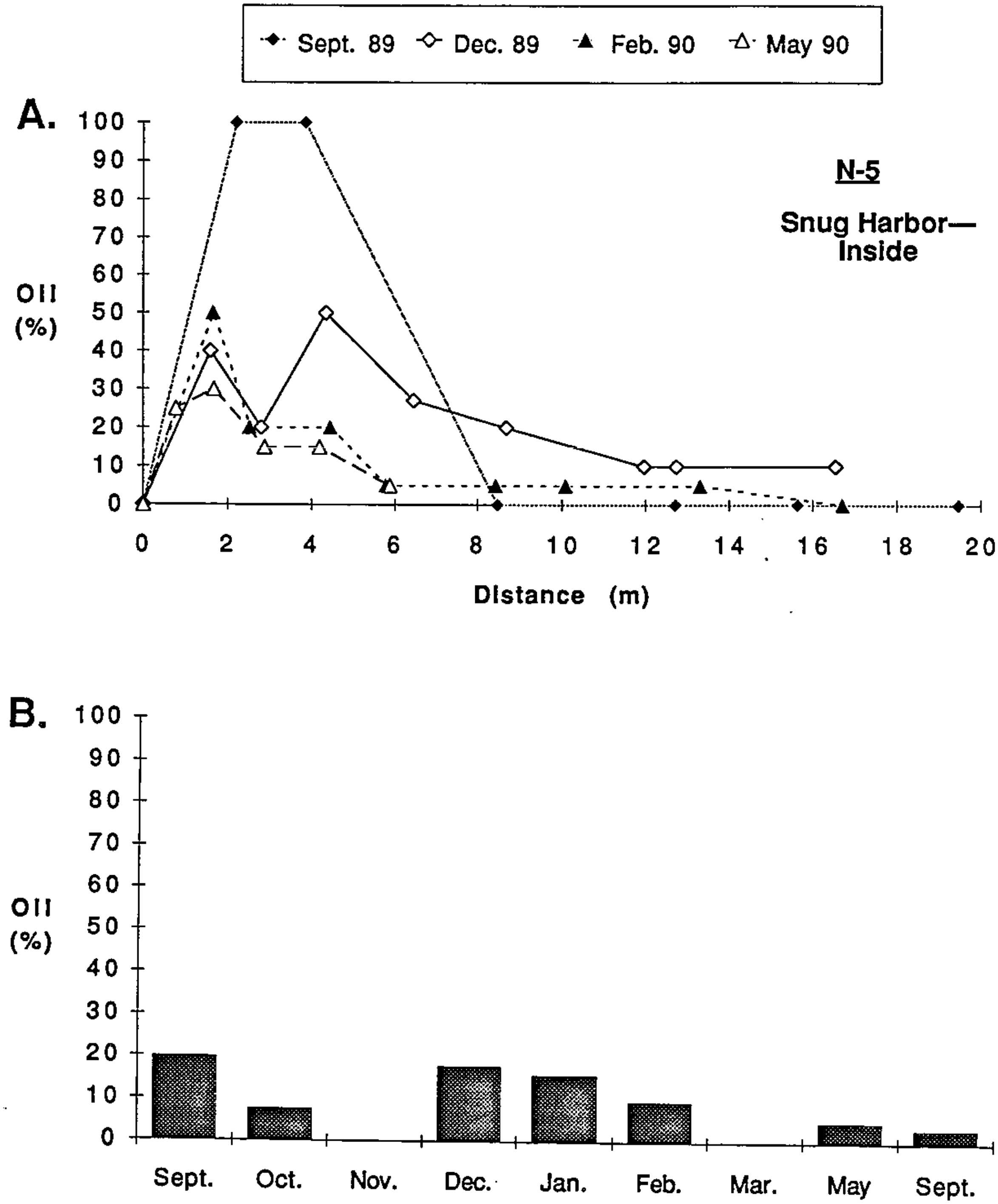


FIGURE 97. Plots of the distribution of surface oil coverage at selected survey periods for station N-5 in Snug Harbor.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 17. Sediment TPH (in ppm) for N-5 on Snug Harbor by morphological zone.

Surface Samples

Date	Rubble Slope	Raised Bay Bottom
9/89	4,970/5,140/41,980	100/430
10/89	1,190/1,330	90
12/89	1,060	80
1/90	36,080	30
2/90	660/5,960	30/150
9/90	410	

Subsurface Samples

	Rubble Slope		Raised Bay Bottom	
Date	< 25 cm	< 25 cm	< 25 cm	< 25 cm
12/89	60/70			20
2/90	60			<10/<10

Station N-13

Introduction. This station is located half way down the eastern shoreline of Herring Bay on Knight Island. The shore is oriented east-west and the beach faces south. There is essentially no effective fetch perpendicular to the beach, the only open water being the entrance to Herring Bay to the north of and behind the beach. Waves entering Herring Bay from the north would have to travel 4.5 km down the bay and bend to the east at right angles and travel another 2.3 km before reaching the beach, where another right angle turn would be required before the waves could approach the beach straight on. This is a highly sheltered area.

The intertidal beach is essentially a rubble-strewn slope adjacent to a raised bay floor, now an intertidal flat. Uplift on this part of Knight Island was around 1.2 m during the 1964 earthquake. The angular sediments generally decrease in size in an offshore direction down the rubble slope, but change from fine to coarse in an offshore direction at the raised bay bottom. A field sketch, beach profile, and surface sediment distribution plot for the station on 27 May 1990 are given in Figure 98 and selected photographs are shown in Figures 99 and 100.

The shoreline was moderately oiled, but it was designated as a set-aside for research purposes and thus was not treated in any manner.

Morphology and Beach Dynamics. This shore has two distinct morphological components:

1) Rubble slope

   Beginning just above the spring high-tide line, a rubble covered surface slopes offshore at a very high angle (14°). The coarse clasts on the surface of the slope are angular to subangular, indicating very little transport by wave action. No depositional features such as berms were observed in this zone.

2) Raised bay bottom

   This unit beings at an abrupt change in slope near the 10 m mark (slope of 7°; Fig. 98B), which also signals a change to finer-grained sediments (down to sand). Widely scattered boulders and bedrock outcrops also occur in this zone, which has a fairly rich epifauna and epiflora.

The beach profile was measured eight times during the study (Table 4), and, needless to say, no significant changes of either the morphology or sediment patterns were noted. Sediment transport on the rubble slope appears to be minimal, but it is possible that the sand and granule material on the raised bay bottom is transported by tidal currents. In any event, no vertical sediment envelope developed on this shoreline.

Sediments. The coarse material in the rubble slope has been transported only a few meters, at most, from its source, the adjacent bedrock highs. The bedrock is composed of metamorphosed basaltic lavas and intrusive mafic rocks (Moffit, 1954). The sediment on the landward side of the raised bay bottom contains up to 60 percent granule and sand, which is subangular and has a heterogeneous composition. The origin of this finer material is uncertain, as it may have been transported some distance. The distribution of surface sediments across the profile, illustrated in Figure 98C, shows the following trends:

1) The sediments on the rubble slope decrease systematically in size in an offshore direction, with boulders decreasing from 50 percent to near zero.
2) The landward half of the raised bay bottom is covered by up to 60 percent sand and granule.
3) Sediments on the offshore half of the raised bay bottom increase in size in an offshore direction, with cobbles and pebbles dominating. This trend may indicate the presence of stronger tidal currents on the outer part of the profile.

Detailed measurements of the size of 40 clasts (mostly cobbles and boulders) on the rubble slope verified the trend discussed above. Comparison of these 40 clasts with the Powers roundness chart (Fig. 19), yielded a ρ value of 2.0, which is on the border between angular and subangular.

At this station, 24 trenches were dug during the course of the study, and the three dug on 27 May 1990 are presented in Figure 101. Armoring per se does not occur in this area, and although the deeper sediments do tend to contain a little more sand and granule material, the sediments are permeable at depth. The deepest oil discovered in the trenches was at 56 cm.

N-13 27 May 90
Herring Bay

A.

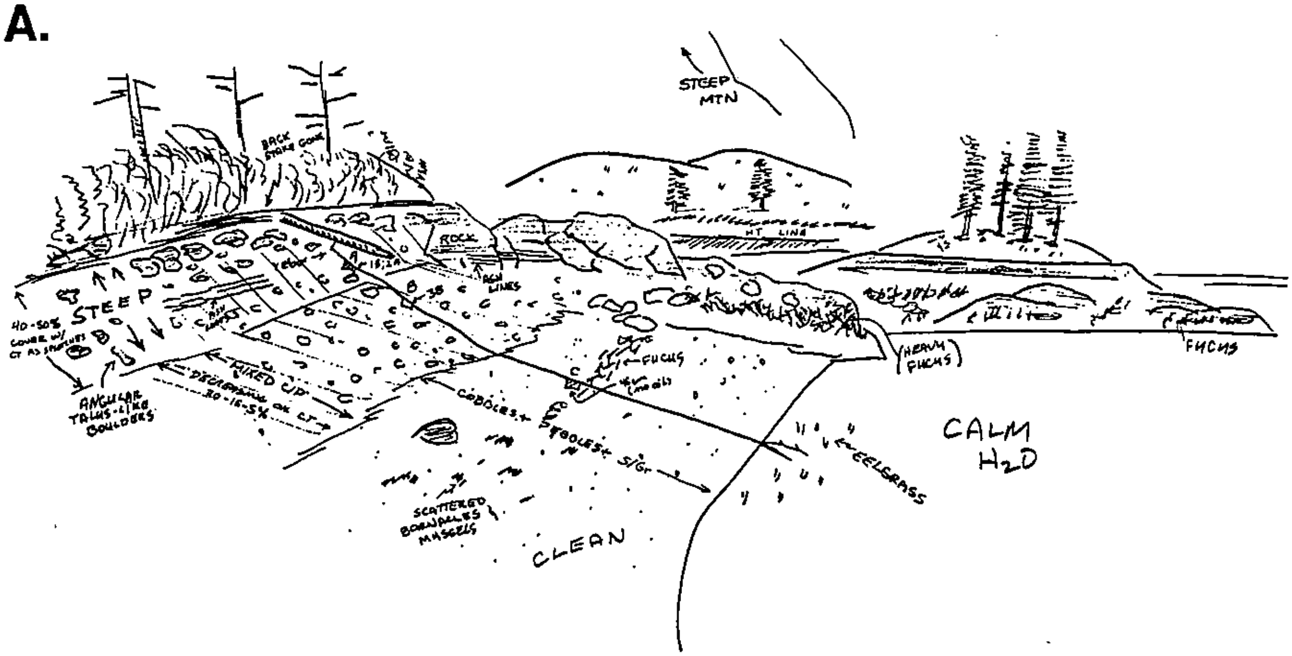
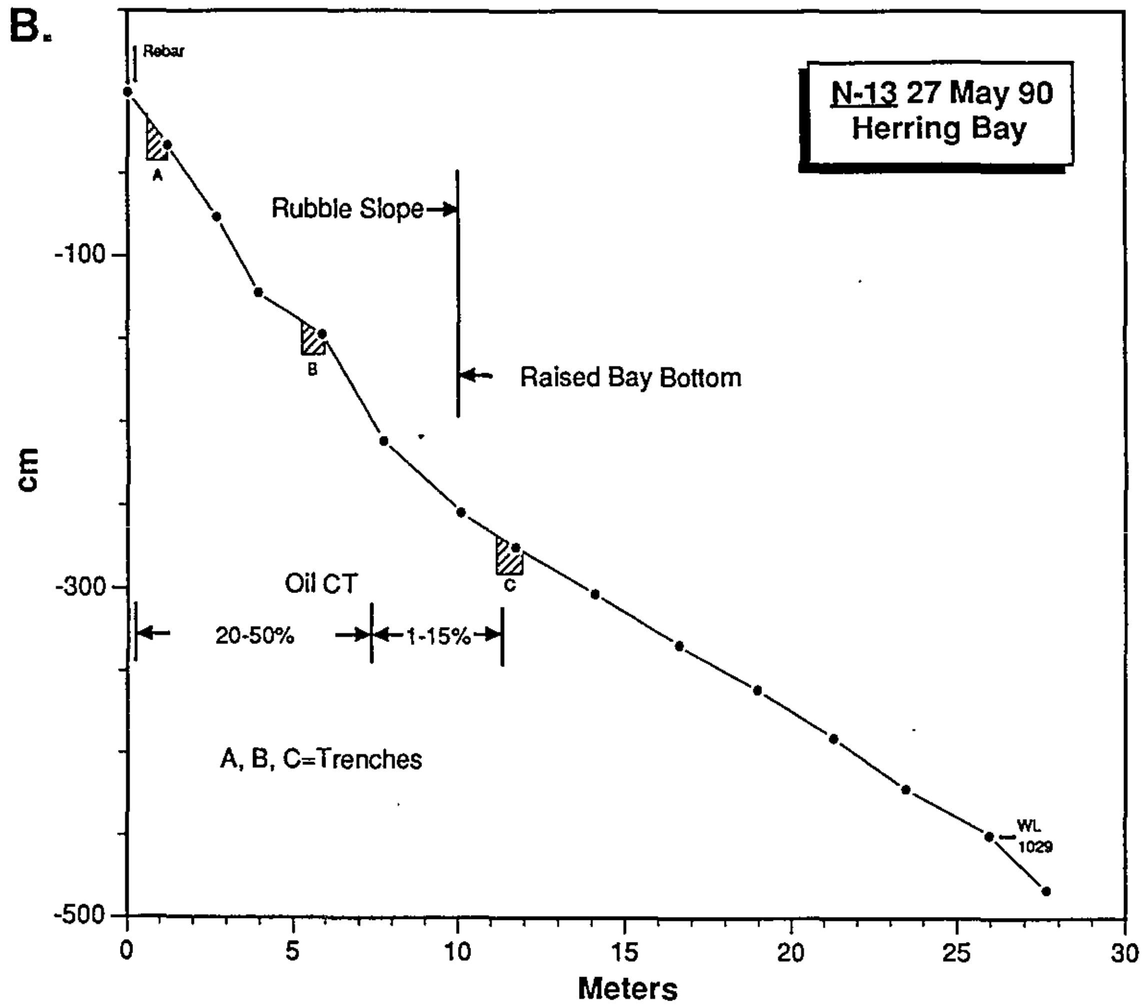


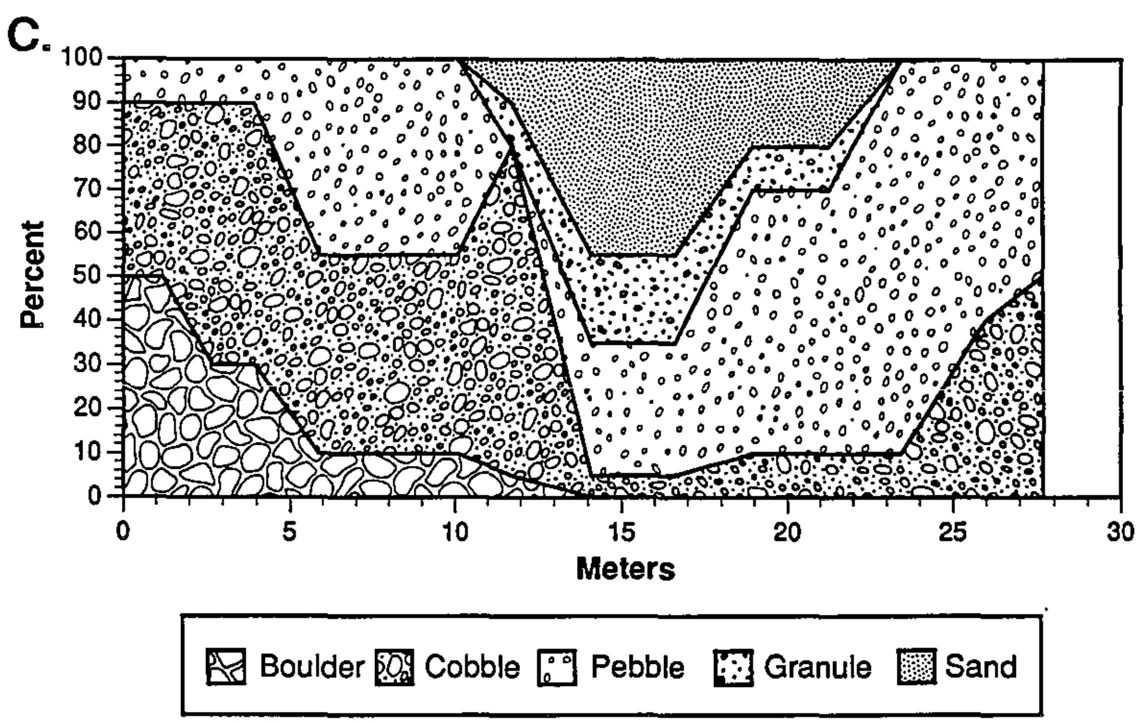
FIGURE 98. Station N-13 on 27 May 199.

A. Field sketch. The contrasting sediment types and slopes of the two subdivisions of the profile, angular talus-like material on the steep rubble slope and finer material on the flatter bay bottom, are evident. Oil cover as high as 50 percent was still present on the upper portion of the rubble slope.

B. Topographic profile, illustrating the clear break in slope between the rubble slope and the raised bay bottom.

C. Distribution of surface sediments based on grain-size estimates at the 14 survey points along the profile (circles shown in B). The two morphological units have opposite grain size trends.


B.
Rebar
N-13 27 May 90
Herring Bay
Rubble Slope
Raised Bay Bottom
A
B
C
Oil CT
20-50%
1-15%
A, B, C=Trenches
WL
1029
cm
-100
-300
-500
0
5
10
15
20
25
30
Meters


C.
Percent
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Meters
Boulder
Cobble
Pebble
Granule
Sand

Oil Distribution Patterns. A steady decrease in surface oil coverage over time is clearly shown in Figure 102. The amount of surface oil in September was reduced by 30 percent by November and 40 percent in January. By September 1990, one year later, the net surface oil reduction was over 80 percent. This trend is clearly shown by the photographs in Figure 99. Because the wave energy level at this site is so low, the oil was reduced by mechanisms other than physical abrasion, such as dessication and tidal flushing. In May 1990, the thick oil coating was observed flaking off the top of the rocks, much like dry, chipped paint (Fig. 100B). The oil coating on the side of the rocks was softer and more resistant to removal. The oil on the top of the rocks, in direct sunlight for the long summer days, was weathering at a faster rate than oil on the sides. We did not see this flaking nature of the oil on treated shorelines, where the thickness of the oil had been reduced by washing with hot water. It appeared that only the thicker coating of oil was subject to such dessication and ultimate flushing by the tides.

The surface sediment chemistry results reflect the variation in oil distribution (Table 18), but do show a trend toward lower levels over time. The 5 September 1990 samples, which yielded very high values, were collected at the high-tide line from crevices that were filled with oil. These thick deposits of oil are sheltered from dessication and will weather very slowly. They did not readily sheen, because the surface had formed a dry skin. The sample with 830 ppm TPH was collected at about the 4 m mark on the profile, and is more representative of the oil levels in the surface sediments.

The extent of subsurface contamination in the rubble slope zone was surprisingly large. In September 1989, a sample from 43 cm deep contained 47,140 ppm TPH, and the oil at this depth was described as fresh looking. In October, a trench in the same area showed free oil to 55 cm, and a trench at the seaward edge of the rubble zone had free oil to 45 cm. Heavy oiling to depths of 40 cm was observed in November and December. Surprisingly, all the trenches dug in January, February, and March revealed no or very light oiling, and the sample results confirm these visual observations. The sudden absence of subsurface oil was perplexing for a while. However, in May, heavy oiling was again observed in trenches A and B (Figs. 98B and 101). Fresh, black oil occurred at 20-25 cm and black oil sheens formed on the water table in trench A. There was less oil in trench B, with a greasy zone from 7-17 cm. No oil was observed in the lower part of the shoreline.

FIGURE 99. (Facing Page) Photographs of station N-13.

A. Westerly view from profile on 15 February 1990. Heavy oil stain coats the coarse, angular boulders. Photo by J. Michel.

B. Slightly more distant view on 27 May 1990 (arrows point to end of same log). Surface coating of oil is somewhat reduced (to 20-50 percent). Photo by M. Hayes.

A.

B.

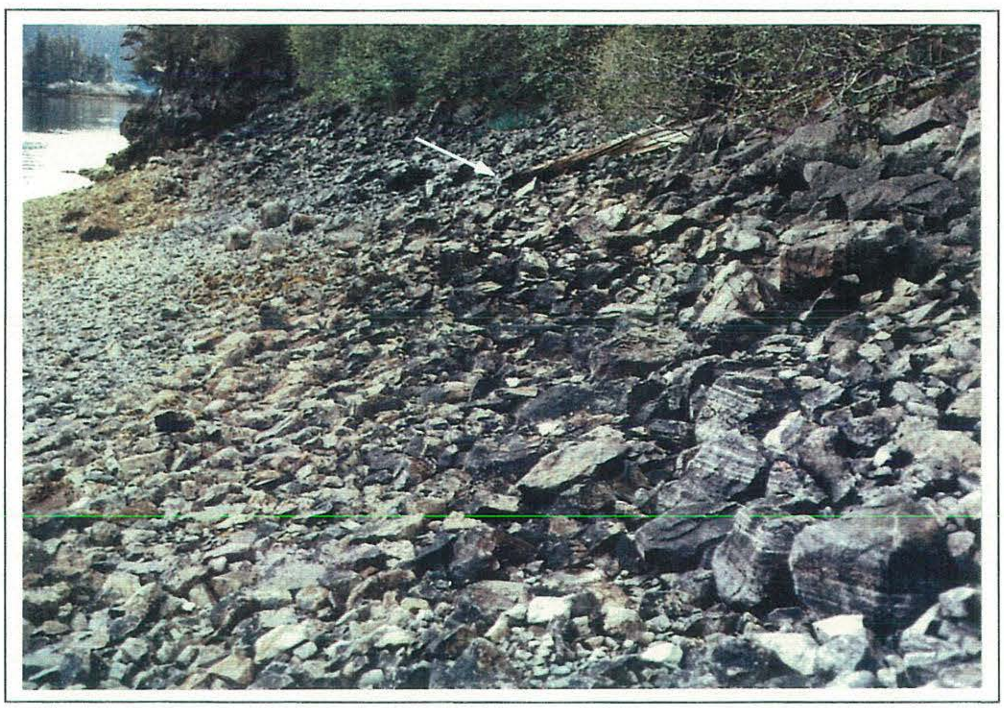
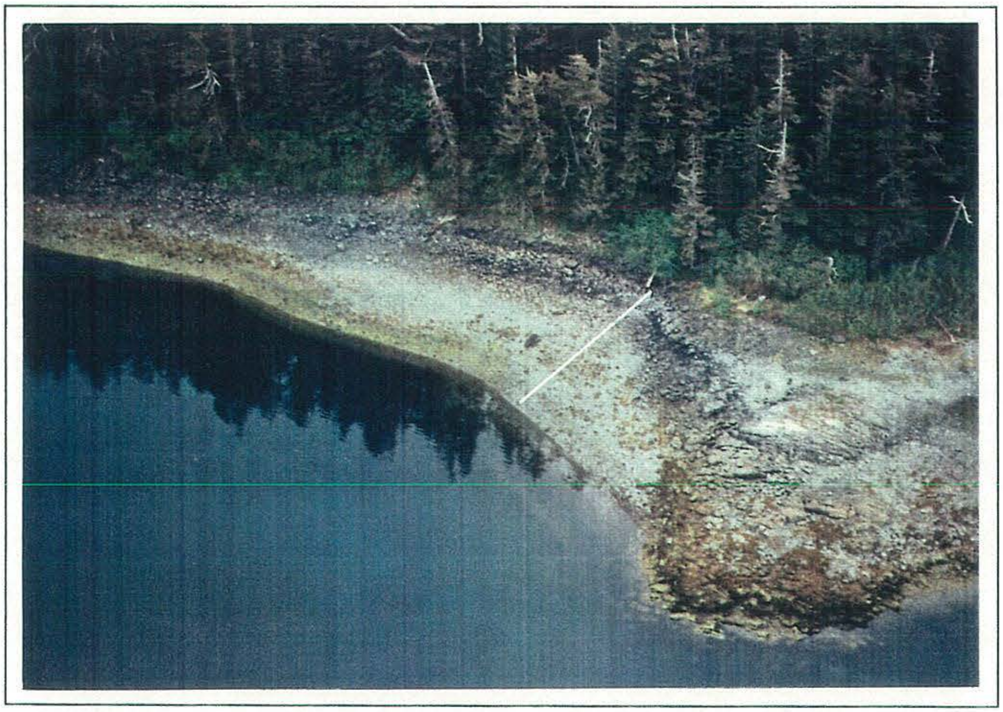


FIGURE 100. (Facing Page) Additional photographs of station N-13.

A. Aerial view on 27 May 1990. Position of permanent profile is indicated. Photo by M. Hayes.

B. Oil peeling off boulders near high-tide line on 27 May 1990. Photo by M. Hayes.

A.



B.

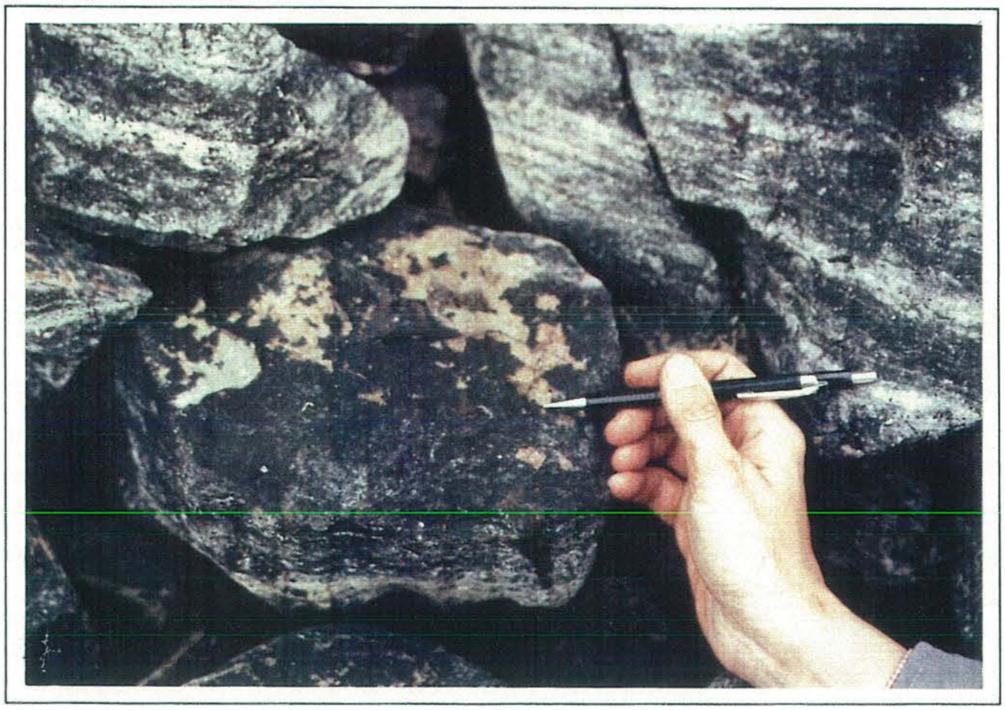


TABLE 18. Sediment TPH (in ppm) for N-13 in Herring Bay by morphological zone.

Surface Samples

Date	Rubble Slope	Raised Bay Bottom
9/89	930/389	
10/89	1,520/20,200	
11/89	2,720/6,930	
12/89	600	
1/90	1,020	80
2/90	60/1,370	120
3/90	20/740	90
9/90	830/10,080/16,700	

Subsurface Samples

	Rubble Slope		Raised Bay Bottom	
Date	< 25 cm	> 25 cm	< 5 cm	< 5 cm
9/89	4,780	820/47,140		
10/89	2,120	50/1,010		
11/89	364	10/210		
12/89	1,930	2,270		20
1/90		40		<10
2/90	<10/60	<10		30
3/90	<10	20		

The highly variable sediment distribution and packing must control the depth of oil penetration. Where the cobbles and boulder are loosely packed, oil readily penetrated to depths of at least 55 cm. In other less permeable areas, the oil pooled on the surface. From a strictly oil-persistence perspective, treatment of rubble slopes would be beneficial in reducing the thickness of the oil on the surface and the potential for deep penetration.

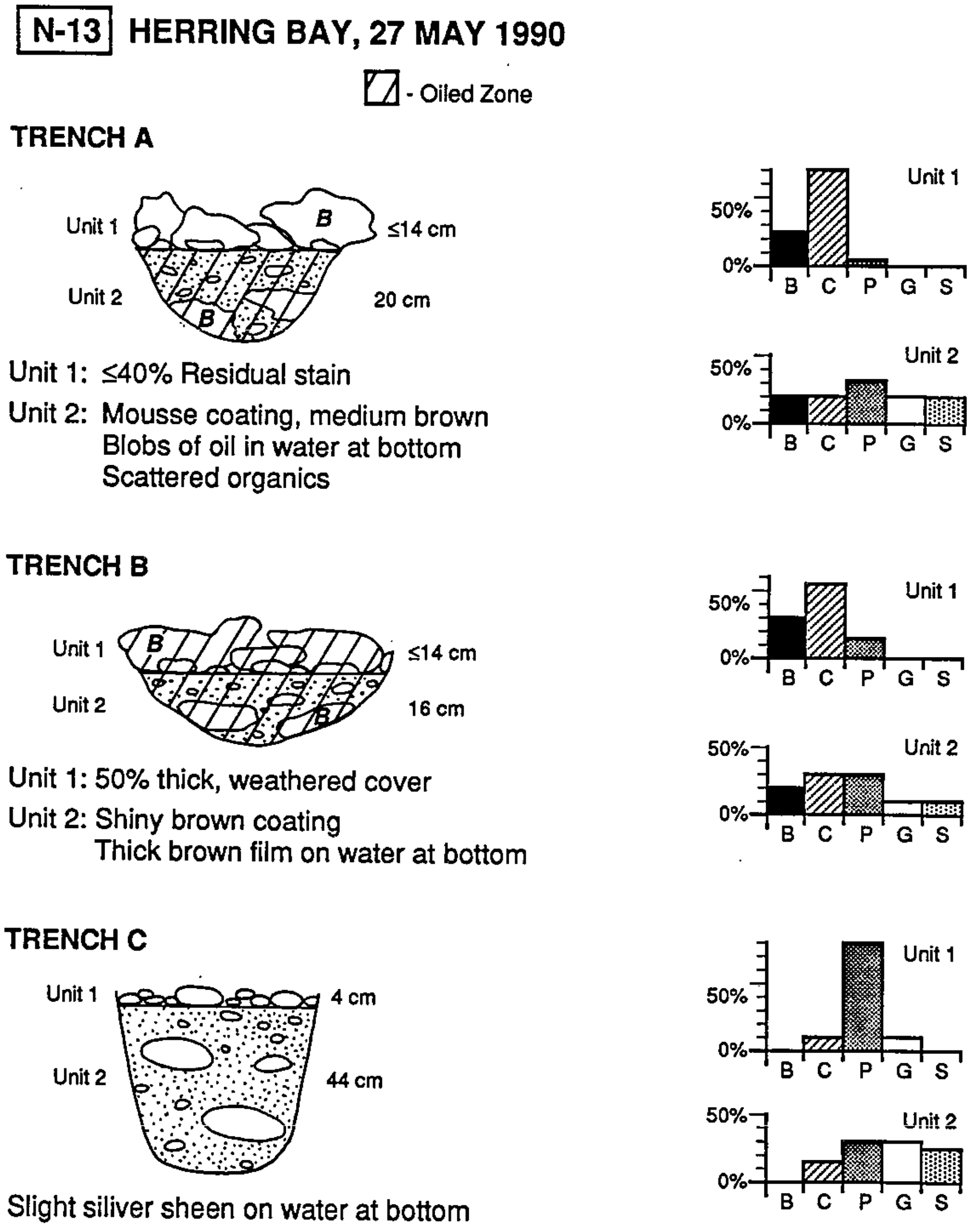


FIGURE 101. Trenches dug at station N-13 on 27 May 1990 (see Fig. 98B for location). The sediments do not have distinct armoring such as that found on the exposed rock platforms (e.g., stations N-1 and N-4), despite the presence of some sand and granules.

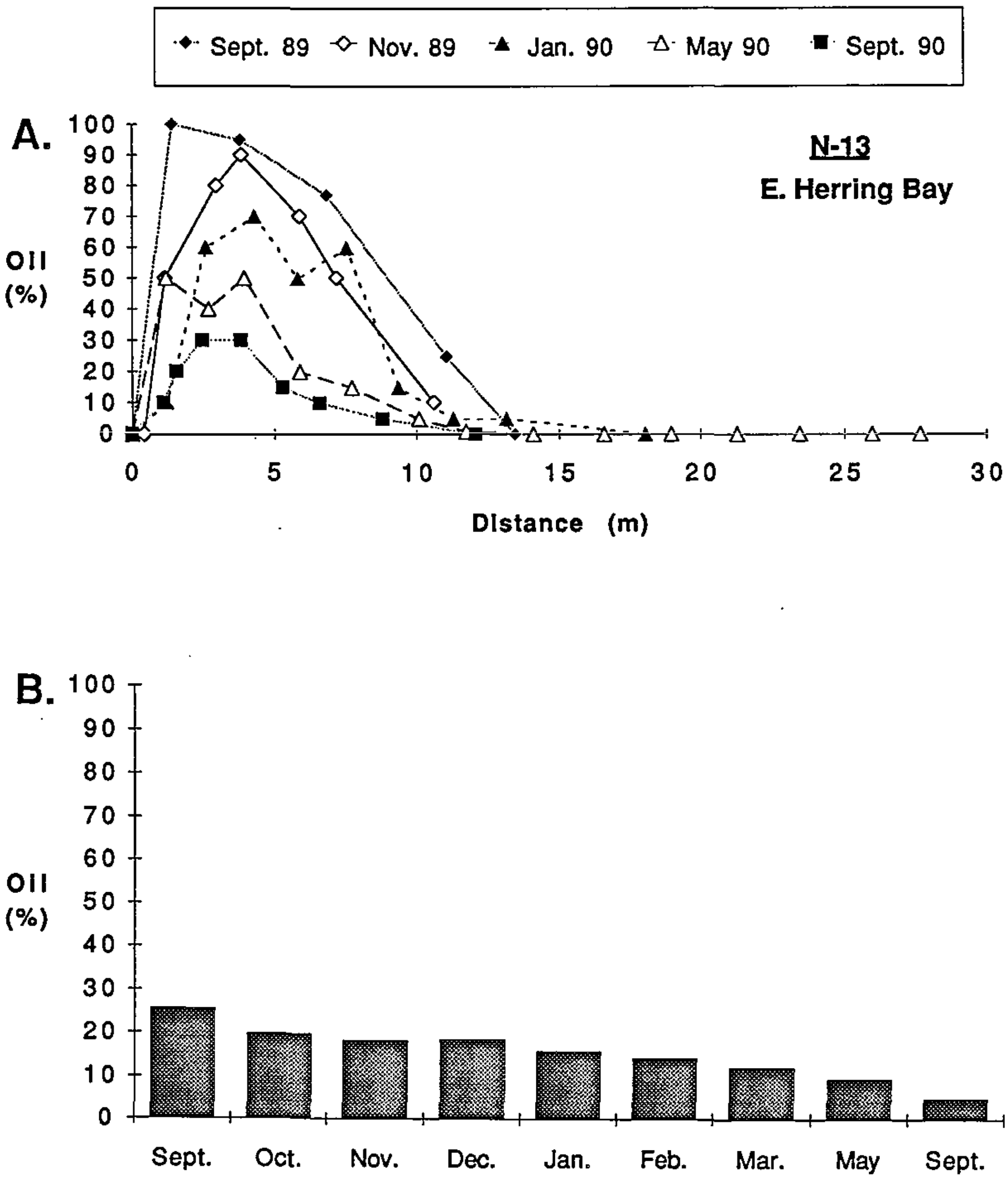


FIGURE 102. Plots of the distribution of surface oil coverage at selected survey periods for station N-13, Herring Bay. This set-aside station still shows oil removal, primarily from the horizontal rock surfaces.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

Station N-12

Introduction. Station N-12 is located on the north side of the same, small circular indention of the west-central coast of Crafton Island that station N-11 is located in. Both stations are shown in the field sketch in Figure 103A. Of course, this station has the same relatively low wave energy as that described for station N-11.

Classification of this station was difficult because it is something of a hybrid, falling between type IV—pebble beaches with tidal flats and type V—rocky rubble slopes with raised bay bottoms. The top of the station is a short, vegetated washover terrace that connects two bedrock highs. An intertidal lagoon is situated behind the washover terrace. Bedrock is close to the surface throughout the upper two thirds of the profile, with the bulk of the rubble at the station being supplied by the two outcrops adjacent to the washover terrace. Uplift recorded during the 1964 earthquake was around 1 m at this site, which accounts for the presence of the uplifted bay bottom at the seaward end of the profile. A field sketch, beach profile, and sediment distribution plot for the station on 31 May 1990 is given in Figure 103.

The station was moderately oiled, and in 1989 it was treated by manual removal and bioremediation (Inipol). Sometime after our survey on 31 May 1990, the remaining asphalt pavements were manually removed, and Inipol and Customblen fertilizer were applied.

Morphology and Beach Dynamics. For purposes of description of this hybrid station, it is divided into three morphological components:

1) Upper beach

   The area from the back stake to around the 12 m mark (Fig. 103B) is apparently washed over occasionally during high spring tides. The washover terrace that connects the bedrock highs was probably formed before the 1964 earthquake. Most of this zone is covered by grasses and driftwood. Pebbles make up the bulk of the surface sediments.

N-12 31 May 90
Crafton Island

A.

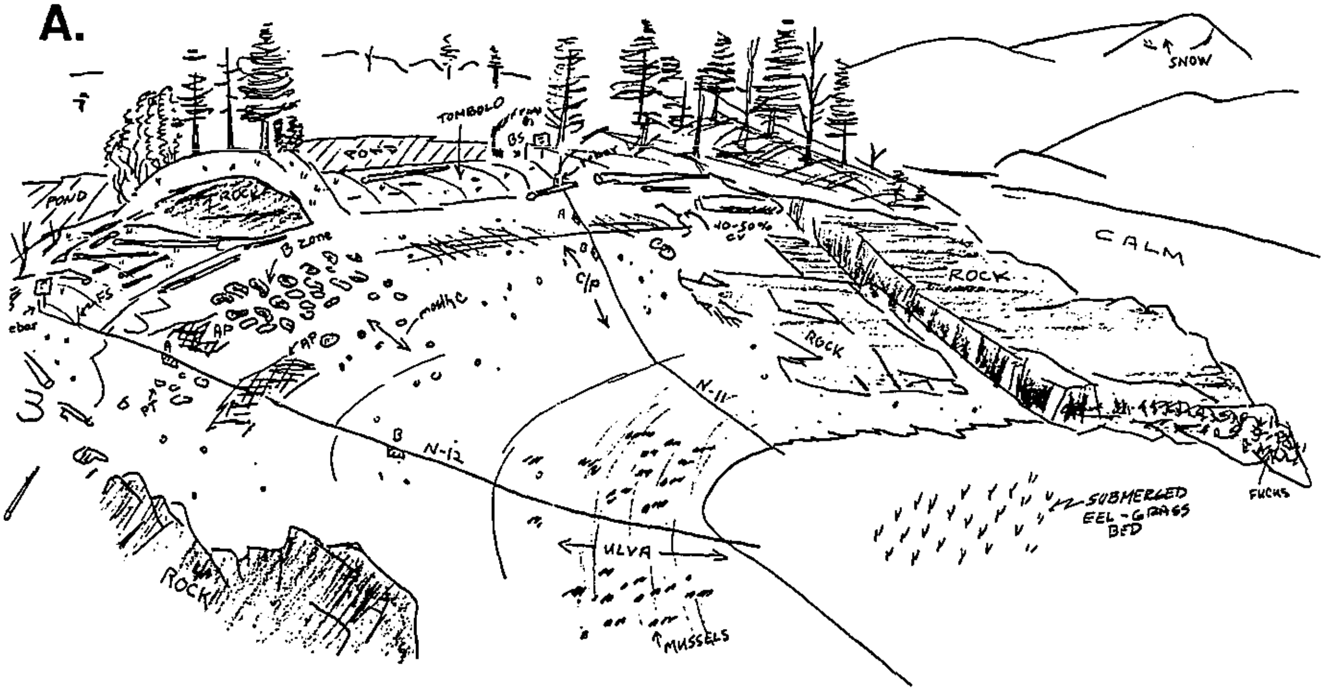
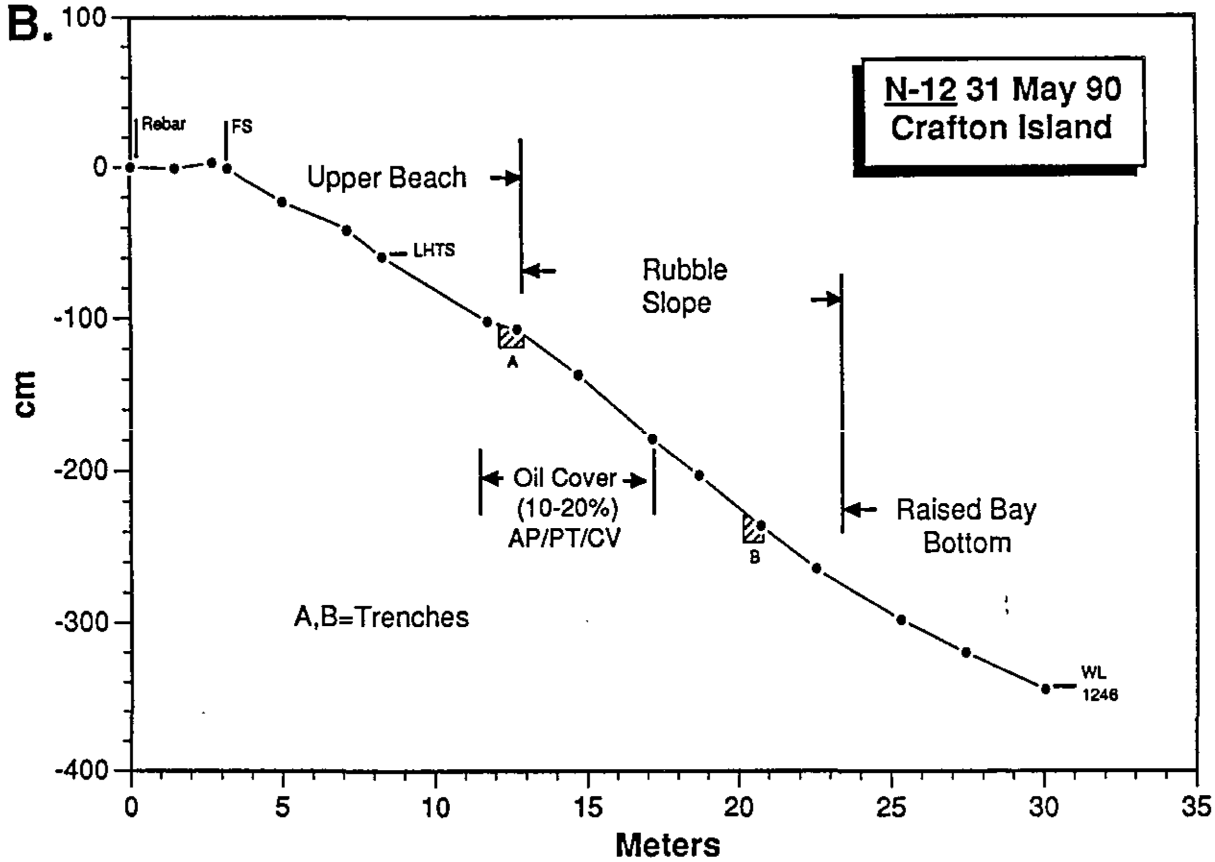


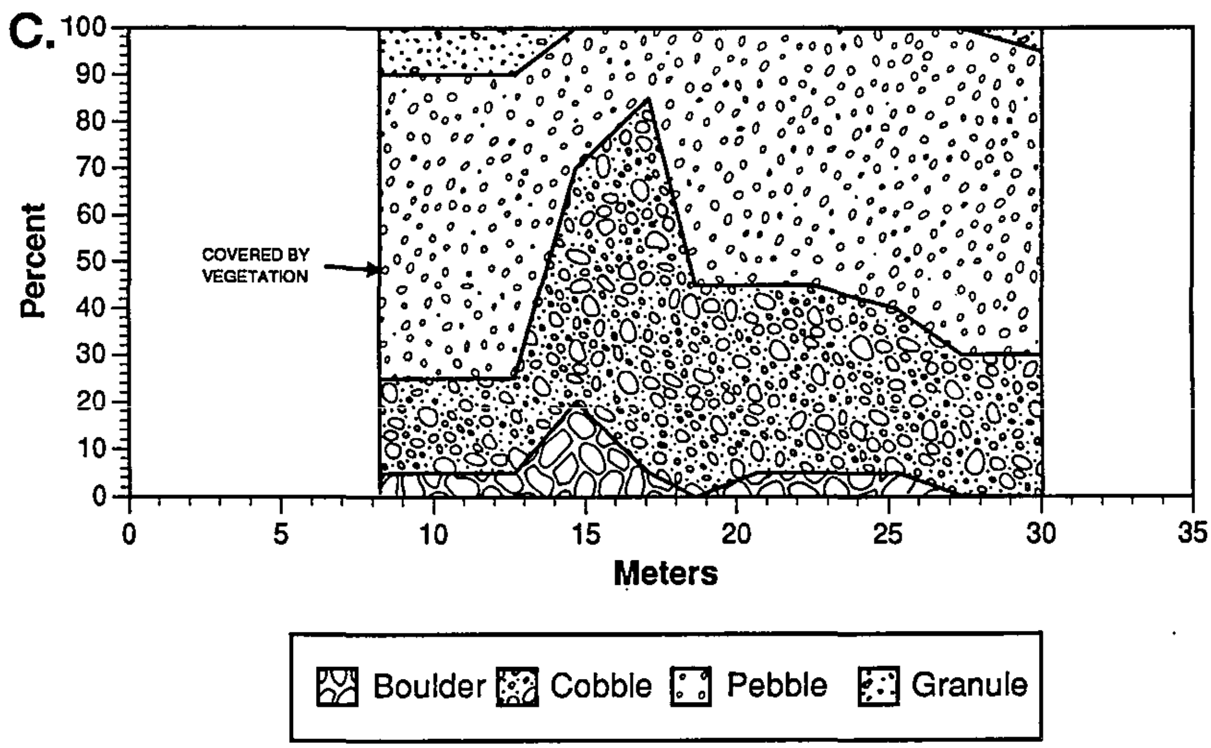
FIGURE 103. Station N-12 on 31 May 1990.

A. Field sketch showing location of this station relative to station N-11. This profile is more influenced by the bedrock and its associated rubble deposit than is station N-11. Note asphalt pavement on the unit we call rubble slope (refer to profile in B).

B. Topographic profile, showing the relative steepness of this profile, as well as its morphological subdivisions.

C. Surface sediment distribution pattern based on visual estimates at 11 of the survey sites (circles on profile in B). Note coarse character of the sediments on the rubble slope. Pebbles dominate both the upper beach and the raised bay bottom.


B.
N-12 31 May 90
Crafton Island
Rebar
FS
Upper Beach
LHTS
Rubble
Slope
A
Oil Cover
(10-20%)
AP/PT/CV
B
Raised Bay
Bottom
A,B=Trenches
WL
1246
cm
Meters
100
0
-100
-200
-300
-400
0
5
10
15
20
25
30
35


C.
COVERED BY
VEGETATION
Percent
Meters
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Boulder
Cobble
Pebble
Granule

2) Rubble slope

Had the profile been placed a few meters to the south, the entire upper part of it would have been a typical rubble slope (refer to sketch in Fig. 103A). Even so, this central unit of station N-12, located between the 12 and 23 m marks (Fig. 103B), has all the characteristics of a rubble slope, including abundant angular boulders and cobbles, a coarse-to-fine offshore sediment size trend, and a near surface bedrock underpinning. The rubble slope dips offshore at 11°.

3) Raised bay bottom

At the time this profile was measured on 31 May 1990, only 7 m of the raised bay bottom, which slopes offshore at 6°, was out of the water. However, it is considerably wider during some spring low tides. Surface sediments average over 60 percent pebbles and have a surface population of Ulva and Mytilus. A lush eelgrass bed is exposed at lower tides.

The profile at station N-12 was surveyed eight times during the study. No perceptible morphological changes could be detected from analysis of the profiles. Although there is no record of it in the field notes, Sexton, Gibeaut, and Balcom (1990; p. 62) state that "between the October and November surveys, a small (10 cm) berm was deposited at the very top of the beach". The berm was composed of "well-sorted pebbles". Except for this one instance, however, there was no evidence of any significant sediment transport at this station during the study.

Sediments. As at station N-11, the sediments at this site were derived from local bedrock outcrops composed of schistose slates and graywackes. The surface sediment distribution plot in Figure 103C shows the following general trends:

1) The upper beach surface is covered predominantly by pebbles, with 20 percent cobbles and minor amounts of boulders and granules.
2) The rubble slope surface shows a general decrease in grain size in an offshore direction. A maximum reading of 20 percent boulders was made in this zone.
3) The raised bay bottom surface exposed on 31 May 1990 averaged 70 percent pebbles and 30 percent cobbles.

A total of 18 trenches were dug on this profile. Trenches were usually quite shallow because of the proximity of the bedrock to the surface. Oil did not penetrate readily into the fine sediments that cover the bedrock.

Oil Distribution Patterns. The oil at this site was restricted to a relatively narrow band at about the 12-17 m interval on the profile (Fig. 104), at an elevation almost 1 m below normal high tides. Part of this oiled zone consisted of an oiled mat which eventually formed a discontinuous asphalt pavement, shown as AP in the sketch in Figure 103A. This oil deposit was routinely sampled during the early surveys (Table 19), and it contained up to 4.3 percent oil by volume. Elsewhere along the profile, TPH levels in surface sediments were relatively low, with 4 samples containing 20 ppm or less. Some oil had been transported onto the upper beach, probably during the October high tides.

One tidal flat sample contained 160 ppm TPH, which was higher than those levels measured at the same elevation along the N-11 profile, although neither area was treated with water-washing techniques. It is likely that this tidal flat continues to be contaminated on the surface, either routinely as oil is mobilized from the upper shoreline or as a result of initial oil deposition at low tide. It will be interesting to follow changes in both oil quantities and weathering trends at this station because it was treated only with manual removal prior to nutrient addition.

Most subsurface sediments were collected from depths less than 25 cm, so no depth distinctions are shown in Table 19. There was very little subsurface oil in the tightly packed sediment veneer on bedrock at the upper beach. The rubble slope had some shallow penetration of oil, with nearly 500 ppm TPH at the 15-20 cm interval. No subsurface oil was seen or measured in samples from the tidal flat, in contrast with N-11 samples, which were collected within 20-30 m distance.

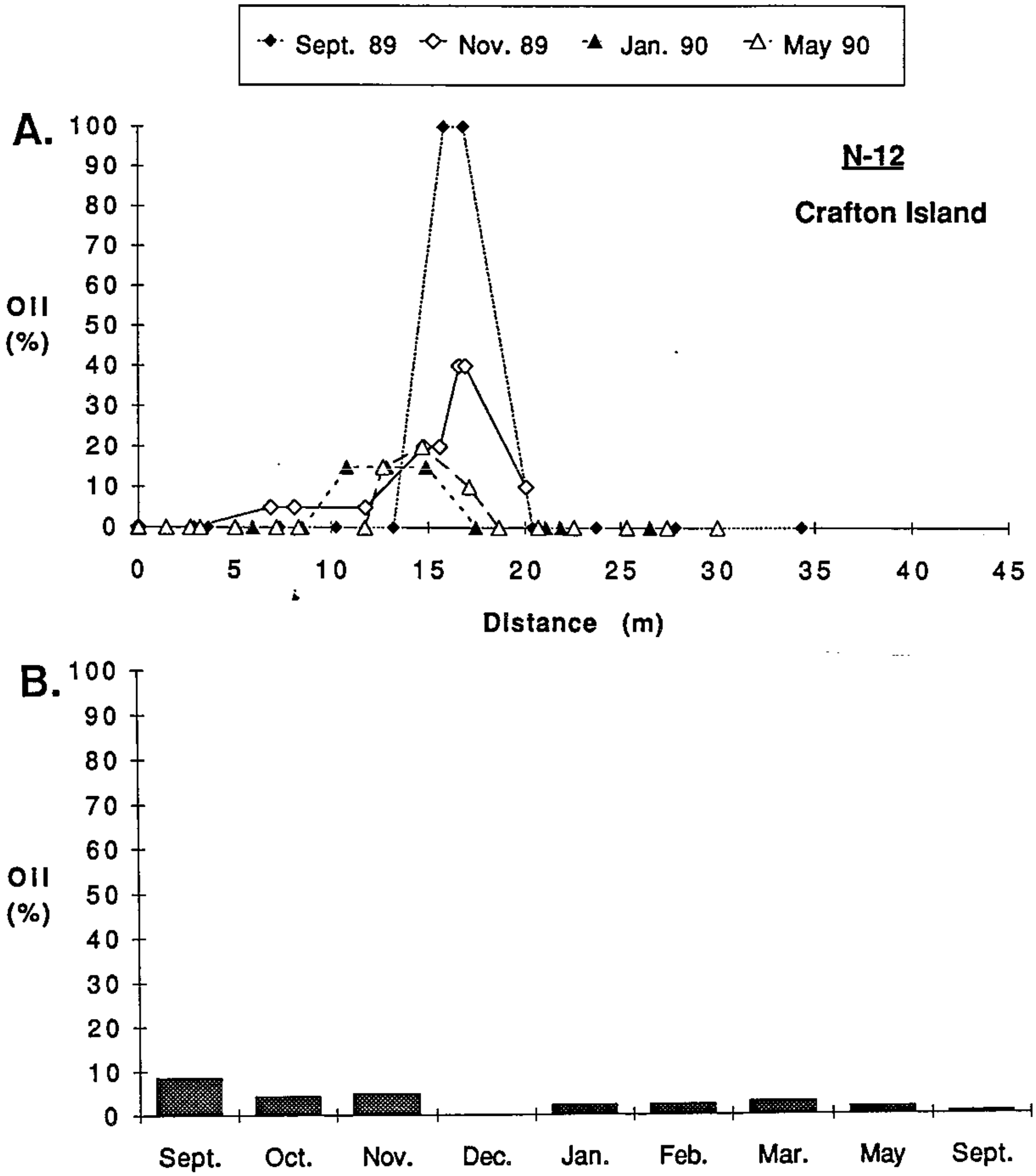


FIGURE 104. Distribution of surface oil coverage for selected surveys at N-12 on Crafton Island. The oil occurred as a definite band which eventually weathered into a broken asphalt pavement. The pavement was removed after May 1990.

A. Plots of the percent coverage of surface oil (visual estimates made in the field) for selected months.

B. Surface oil coverage, integrated over the entire profile, for each month.

TABLE 19. Sediment TPH (in ppm) for N-12 on Crafton Island by morphological zone.

Surface Samples

Date	Upper Beach	Rubble Slope	Raised Bay Bottom
9/89		30,210*	
10/89		9,970*	
11/89	110/120	28,210*	
1/90	50	16,250*	20
2/90		4,610	<10
3/90	10	<10/380	160
9/90		17,880*	

* Asphalt pavement

Subsurface Samples

Date	Upper Beach	Rubble Slope	Raised Bay Bottom
9/89	91		
10/89		70	
11/89		30	
1/90	10	480	10
2/90		140	10/10
3/90	10	110	

SHELTERED ROCKY COASTS

General Description of Shoreline Type

According to our ESI data, 32 percent of the PWS shoreline oiled by the EXXON VALDEZ spill is sheltered rocky coasts. Three of the NOAA permanent stations—stations N-10 in Herring Bay, N-6 in the Bay of Isles, and N-16 on Applegate Island—are located on this coastal type. These shorelines usually are quite complex and in many instances have associated heavily oiled tombolo deposits. Data can be as varied as the many possible directions one desires to run a sampling profile across the rocks. Therefore, it is difficult to make simple generalizations about this type of shoreline, which usually has a rich community of marine organisms associated with it. The Bay of Isles site is a set-aside.

Station N-10

Introduction. This is a bedrock-dominated station located on a north-south oriented, slight indention in the coast on the east side of the entrance to Herring Bay, Knight Island (Fig. 16). It is a moderately exposed coast with an effective fetch in a westerly direction of 10 km. Open water to the northwest provides an effective fetch line of 25 km that strikes the coast at a 60° angle. As seen from the sketch in Figure 105A, a small tombolo composed of pure pebbles has formed in the lee of a major bedrock outcrop on the profile. Even as late as 27 May 1990, the surface of the tombolo had 100 percent oil coverage (Fig. 106B). This area was uplifted 1.2 m during the earthquake of 1964.

Through some communication error, at least two different profile lines were run at this site at various times, one perpendicular to the beach and straight over the large bedrock mass (labeled 10-X on Fig. 105A), and the other at an oblique angle to the beach oriented northwest down a small draw through the bedrock (labeled N-10 on Fig. 105A). As best we can tell from the field sketches and notes, a profile was run in the vicinity of what we call N-10X four times during the study and along N-10 five times. Both N-10 and N-10X were measured on 27 May 1990 and they are presented in Figure 105 (B and C). Two photographs of the site are given in Figure 106.

The shoreline was heavily oiled, and subsequently it was treated with hot-water flushing in June-July 1989. The pebble zones were bioremediated as well. In

N-10 27 May 90
Herring Bay

A.

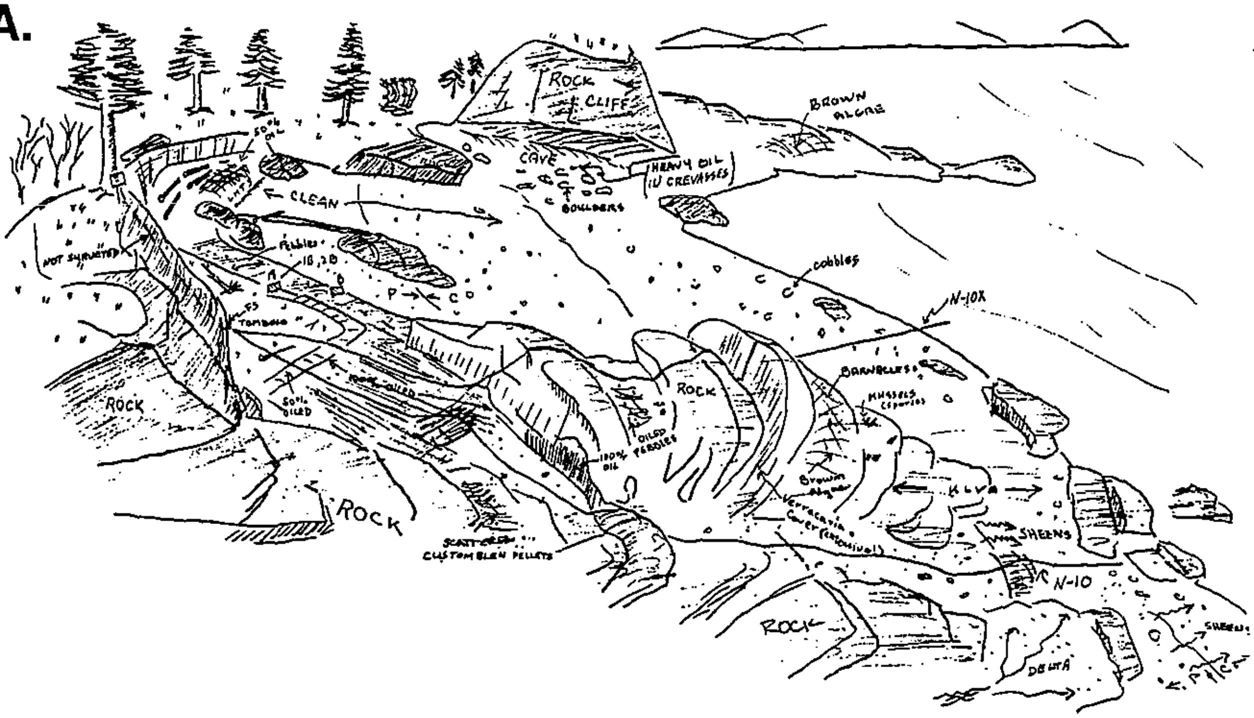
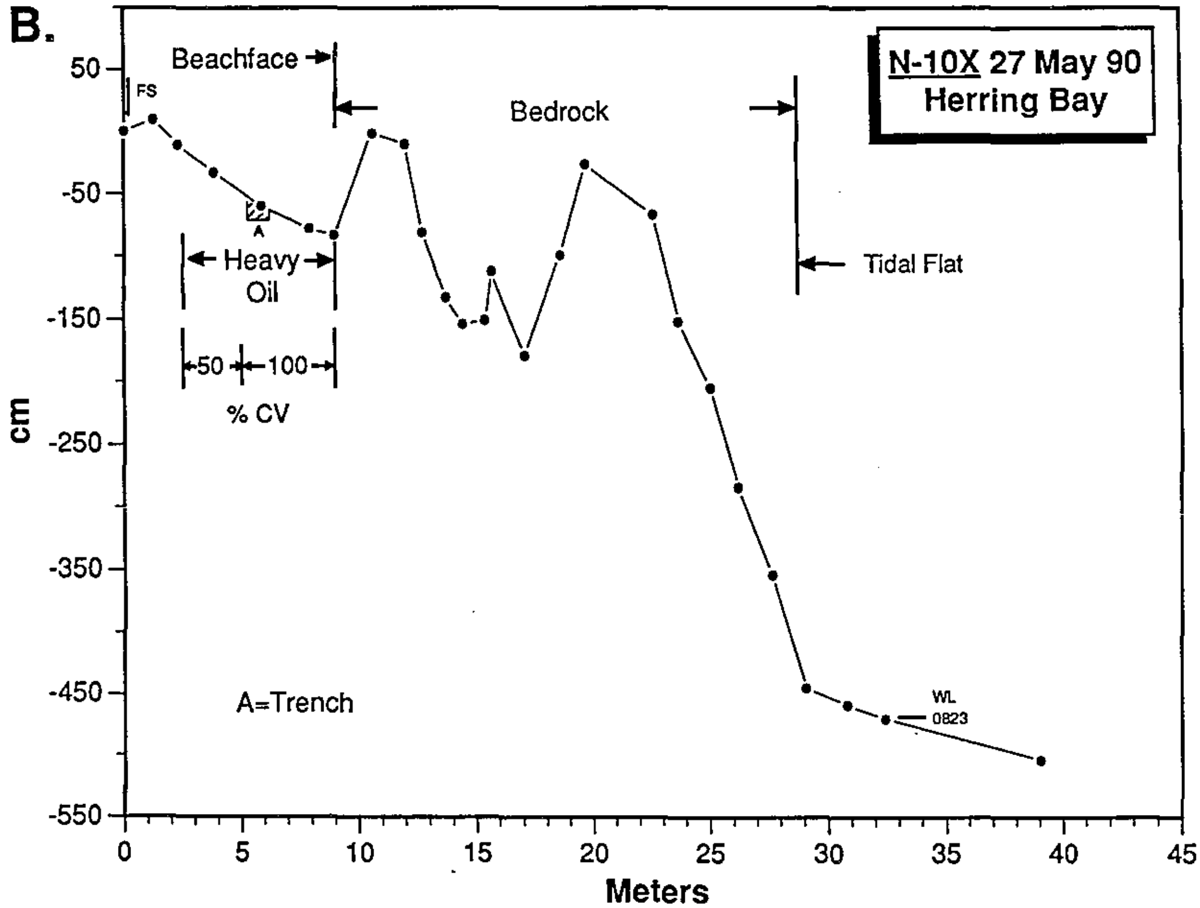


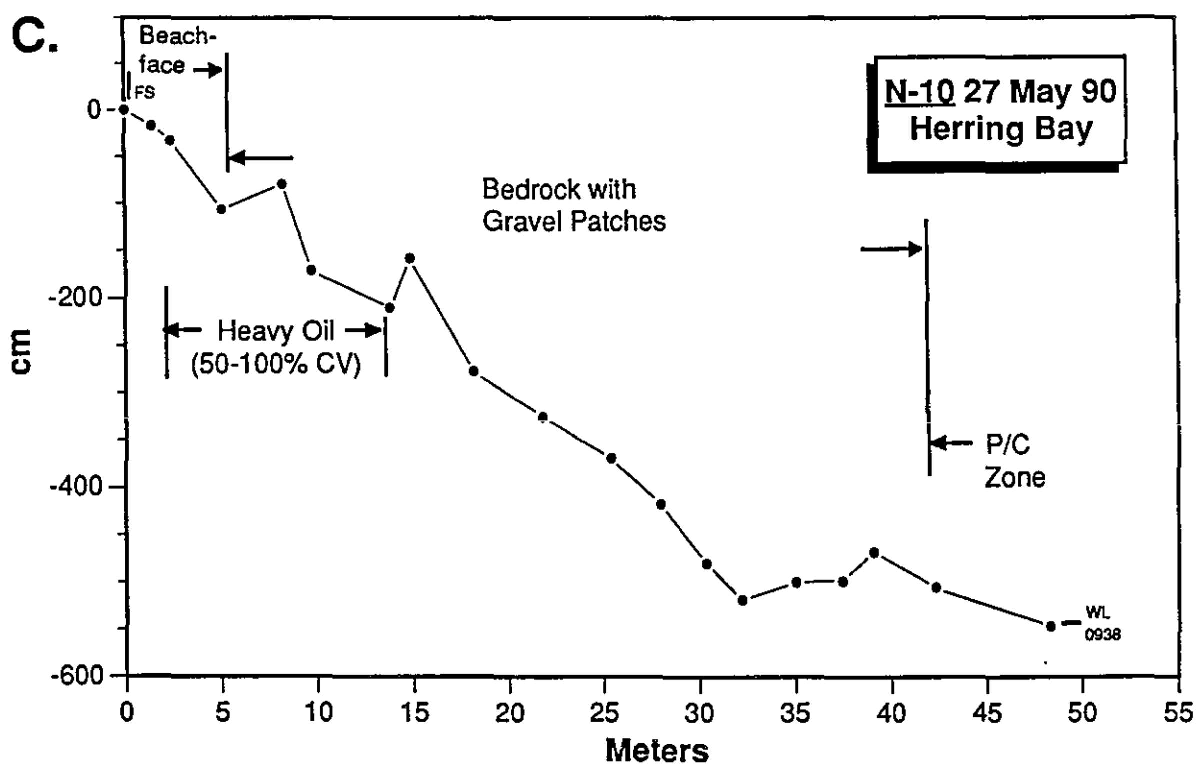
FIGURE 105. Station N-10 on 27 May 1990.

A. Field sketch. The two profiles shown, N-10 and N-10X, were surveyed on this day and are presented in this figure (B and C). Heavy oil remained on the surface of the pebble tombolo. Heavy sheening was observed in the foreground where a stream was draining through a gravel beach behind the observer.

B. Topographic profile N-10X, which was run perpendicular to the shoreline. Tombolos such as the one shown here were one of the most common sites of surface oil retention at the EXXON VALDEZ spill site. This profile is a truer representation of the morphology of the shoreline than the one shown in C.

C. Topographic profile N-10. The original survey line established on 19 September 1989 and the one run most often during the study.


B.
N-10X 27 May 90
Herring Bay
Beachface
Bedrock
Tidal Flat
FS
A
Heavy Oil
50
100
% CV
A=Trench
WL
0823
cm
Meters
50
-50
-150
-250
-350
-450
-550
0
5
10
15
20
25
30
35
40
45


C.
N-10 27 May 90
Herring Bay
Beach-
face
FS
Bedrock with
Gravel Patches
Heavy Oil
(50-100% CV)
P/C
Zone
WL
0938
cm
Meters
0
-200
-400
-600
0
5
10
15
20
25
30
35
40
45
50
55

1990, there was a debate on how to treat the heavily oiled pebbles on top of and to the sides of the bedrock. A combination of techniques was finally used, consisting of removal of some sediments and treatment of the rest with Inipol and Customblen.

Morphology and Beach Dynamics. The morphology of profile N-10X, which was run perpendicular to the beach like all the profiles previously described, can be conveniently subdivided into three morphological components (Fig. 105B):

1) Tombolo

   This is an oil-covered pebble berm that was deposited in the lee of the large rock outcrop. Judging by the lack of reworking of the oil, the berm did not change much over the study period. The beachface of the berm slopes seaward at 7°, an unusually low angle for sediments of this size.

2) Bedrock

   An abundance of attached flora and fauna (e.g., *Fucus*, barnacles, mussels, *Ulva*, etc.) cover this large, complex bedrock mass.

3) Tidal flat

   This gently dipping surface is covered with roughly equal quantities of pebbles and cobbles, as well as a few boulders and some granules.

FIGURE 106. (Facing Page) Photographs of station N-10.

A. Oblique aerial view looking south on 26 May 1990. Note oil-covered tombolo directly behind the rocks. Arrow points to location of photo shown in B. Oil was buried to depths exceeding 60 cm in the pebble beach at the bottom of the slide as a result of berm accretion. Photo by M. Hayes.

B. Oiled pebbles on the surface of the tombolo on 26 May 1990. Photo by M. Hayes.

A.

B.

The rounded nature of the pebbles on the tombolo indicates that considerable sediment transport can occur in that area during a major storm. However, this apparently did not happen during the period of our study. A classic reflective gravel beach, made up of several levels of pebble berms, occurs a few meters north of the NOAA station (see aerial view in Fig. 106A). We found oil buried at a depth of 62 cm near the mid-tide level of this beach on 26 May 1990, even though the surface sediments were clean. On that same day, we saw considerable sheening at the toe of the beach as a result of drainage of a small stream through the beachface. Therefore, the poten-tial for a significant vertical sediment envelope to develop with concomitant oil burial is present on the gravel beaches of this coastal segment.

Altogether, 23 trenches were dug at this station. Every trench dug contained buried oil.

Oil Distribution Patterns. The entire intertidal zone at this station was heavily oiled throughout the fall and winter surveys (Fig. 107). The pebble tombolo and pockets of pebbles in bedrock crevices were covered with a brown mousse. The bedrock surface itself was nearly 100 percent covered with thick oil. It was as though this rock outcrop was missed during the 1989 cleanup. Also, sheens were always seen leaching out of the steep pebble beach just to the north of the bedrock, where a small stream drained through the porous and heavily oiled pebble berm. Oil was found to 62 cm in the pebble tombolo behind the bedrock as well; a sample collected in November from 52-62 cm depth contained 430 ppm TPH (Table 20). The surface of these pebble deposits on the bedrock remained heavily oiled until cleanup activities in July 1990, when the oiled sediments were removed and the area was treated with both Inipol and Customblen.

The bedrock remained heavily oiled through at least March 1990 (Fig. 107); however, by late May, oil remained primarily in the vertical bedrock faces and in crevices. The horizontal surfaces most exposed to the sun and waves were relatively clean. The sheens being released from the adjacent beach did not appear to adhere to the bedrock or attached vegetation, but reoiling of this area with black oil did occur at times. The survey teams routinely reported the presence of both a dull, weathered oil coat or stain and a shiny black tacky oil coat at various elevations. Wave refraction around the bedrock headland would tend to accumulate and trap oil being eroded from adjacent areas. Spruce needles were also trapped by wave refraction and adhered to the sticky oil surface on the vertical bedrock. This station is a good example of the microenvironments which tend to

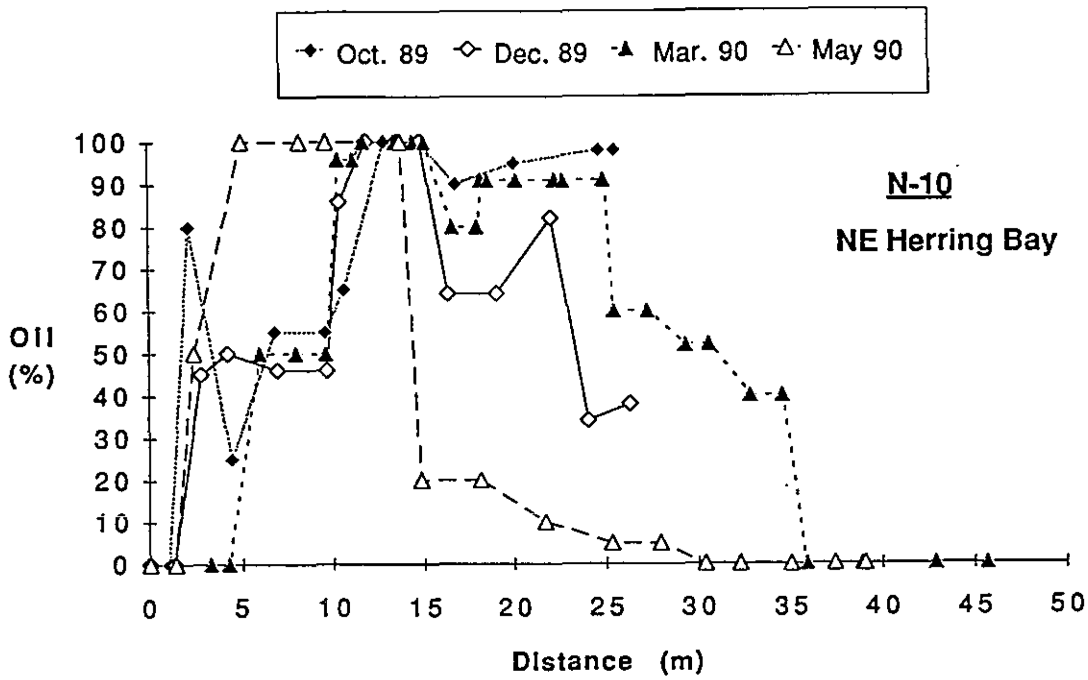


FIGURE 107. Plot of the surface oil coverage at N-10 on Herring Bay for selected surveys. Note the persistence of oil on both the pebble and bedrock surfaces.

accumulate or retain oil along a complex shoreline. The pebble beaches to the north and south of the bedrock were surficially clean, yet the pebble pockets in the bedrock were heavily oiled throughout. Because these pockets are isolated from regular tidal flushing and reworking by waves, persistence of oil will be long term.

The tidal flat at the base of the bedrock is covered with cobbles and pebbles. Sheens were commonly seen on the sediments, although the source of the sheens was most likely the stream discharge through the adjacent beach. The sediments were oiled in September 1989, both on the surface (480 ppm) and with depth (5,220 ppm at 25 cm). A large accumulation of mussel shells covered the surface of the flat. The flat was not surveyed again until December 1989 (because of high low tides), when light oil on the pebbles was noted and a sample from 18-26 cm contained 120 ppm TPH (Table 20). In February 1990, light oil was observed to 18 cm depth in the tidal flat, and in March 1990, sheens were seen in the trench, with 130 ppm TPH in a surface sample and 20 ppm in sediments from 20 cm. Because of the constant source of sheens from the adjacent beaches, the lower intertidal zone in this area continued to be contaminated. The oil in these sheens was relatively fresh because of the deeply buried source.

TABLE 20. Sediment TPH (in ppm) for N-10 in Herring Bay by morphological zone.

Surface Samples

Date	Pebble Tombolo	Bedrock	Tidal Flat
9/89	50	760/6,130/40,810	480
10/89	2,520/4,510		
11/89	830	6,960	
12/89	760/3,520		
1/90	1,820		
2/90	780	4,610/230/620	
3/90	3,000	510	130
9/90	780/1,710	1,340/3,010	

Subsurface Samples

	Pebble Tombolo		Tidal Flat	
Date	< 25 cm	> 25 cm	< 5 cm	< 5 cm
9/89	4,360	1,090		5,220
10/89		660/9,630		
11/89		430		
12/89	2,510	1,170/6,980		120
1/90	270	170		
2/90	190	620		
3/90	1,670	150/1,060		20

Station N-6

Introduction. This station is a steep, south-facing protuberance of bedrock located near the head of the west arm of the Bay of Isles on Knight Island. The location is quite sheltered from wave action. It is less than 1 km across the bay to the south and 7 km to the entrance of the bay by an indirect route. There is, however, an effective fetch of 2.5 km in an easterly direction down the open bay (see sketch in Fig. 108A). The profile was run down a small draw between two bedrock highs which had a cover of loose debris composed of 40-50 percent angular boulders. This site was uplifted around 1.2 m during the 1964 earthquake. A field sketch, beach profile, and sediment distribution plot for the station on 31 May 1990 are given in Figure 108 and two photographs are given in Figure 109.

The bedrock shoreline at station N-6 was moderately oiled. To the west, where the NOAA biological monitoring site is located, the shoreline is flatter, covered by a veneer of cobbles and boulders, and was lightly oiled. The N-6 profile is located about mid-point of the area designated as a set-aside, therefore no shoreline treatment has been conducted.

Morphology and Beach Dynamics. No attempt was made to subdivide this station into morphologic units because it is a relatively homogeneous bedrock outcrop. Of course, the usual biological zonation is found at the different tidal levels on the bedrock surface.

The beach profile was surveyed only three times during the fall and winter period (Table 16), because, according to Sexton, Gibeaut, and Balcom (1990; p. 40), during the February and March surveys the "beach was buried under large sheets/blocks of ice". The station was revisited on 31 May 1990 and 4 September 1990. There were no changes in the beach morphology during the survey period and beach dynamics are nil.

Sediments. The sediment debris that occurs on this profile is there because of normal weathering processes acting on the bedrock, which is composed of "greenstone", a general term for basaltic lava flows and mafic intrusive rocks, which contain an abundance of iron-bearing minerals. The grain size of the surface material, which was measured during the 31 May 1990 survey (Fig. 108C), shows a slight increase in size in an offshore direction. Boulders increase and pebbles decrease in abundance down slope, with cobbles making up around one-third of this angular sediment throughout. Eleven trenches were dug at this site during the

N-6 27 May 90
Bay of Isles

A.

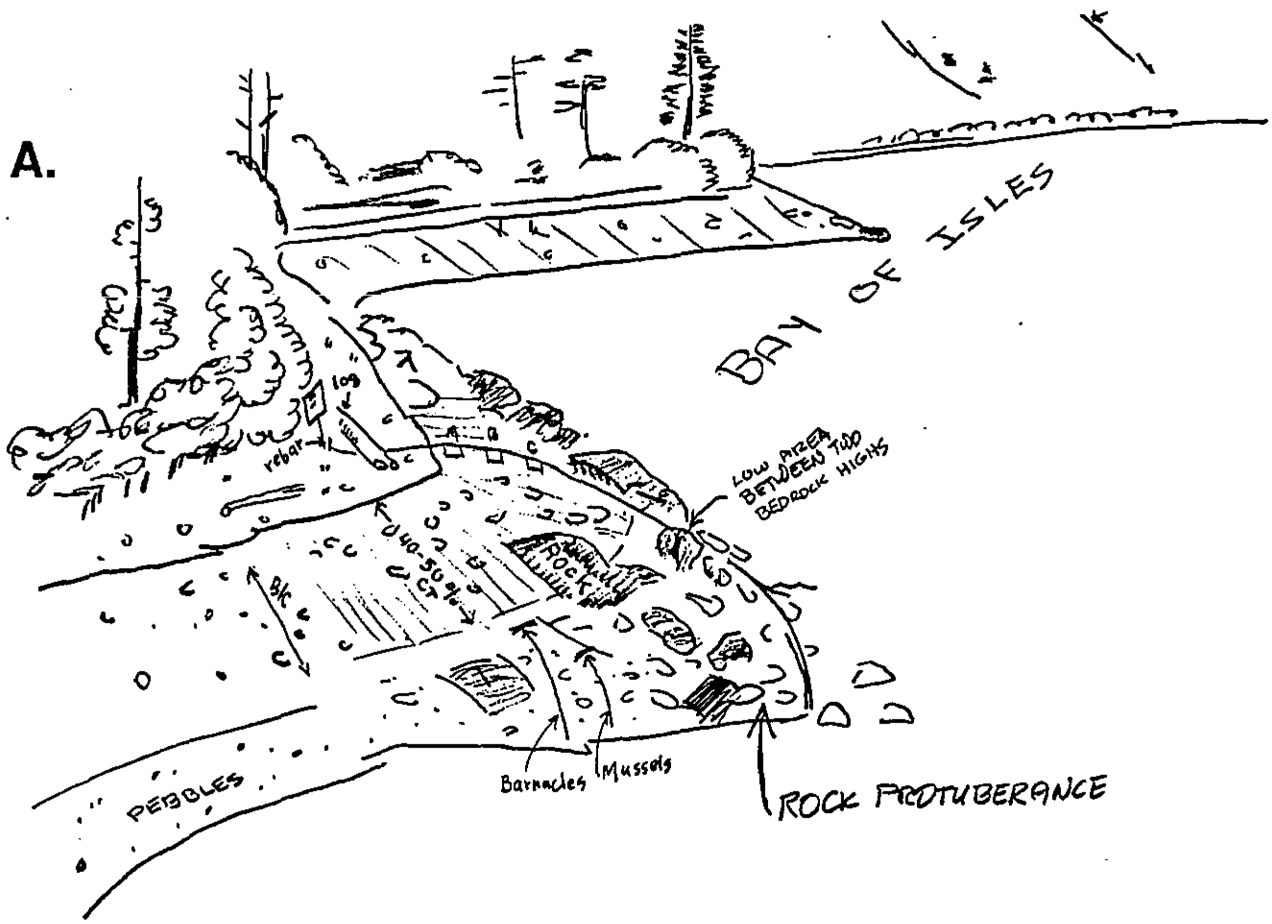
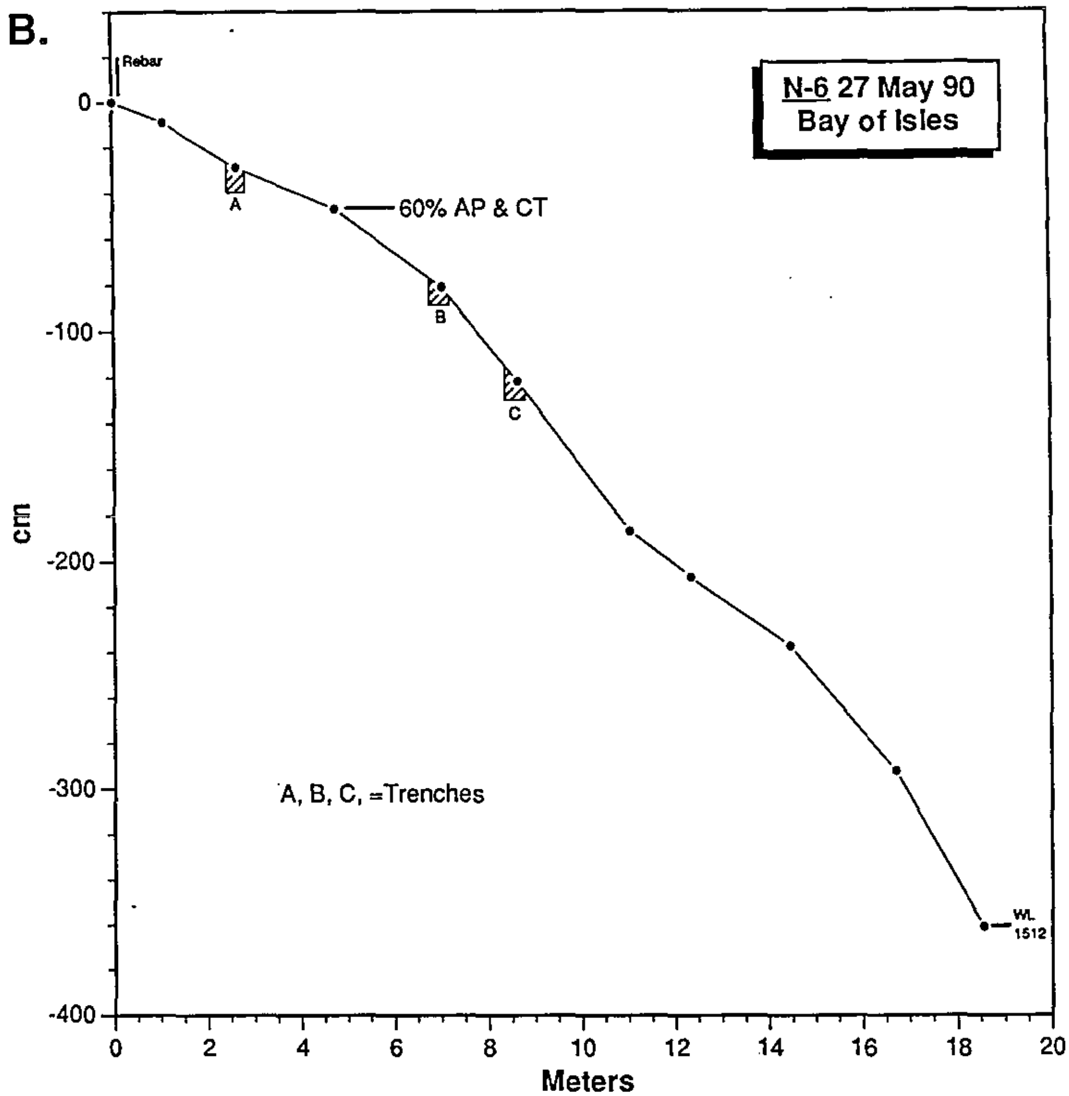


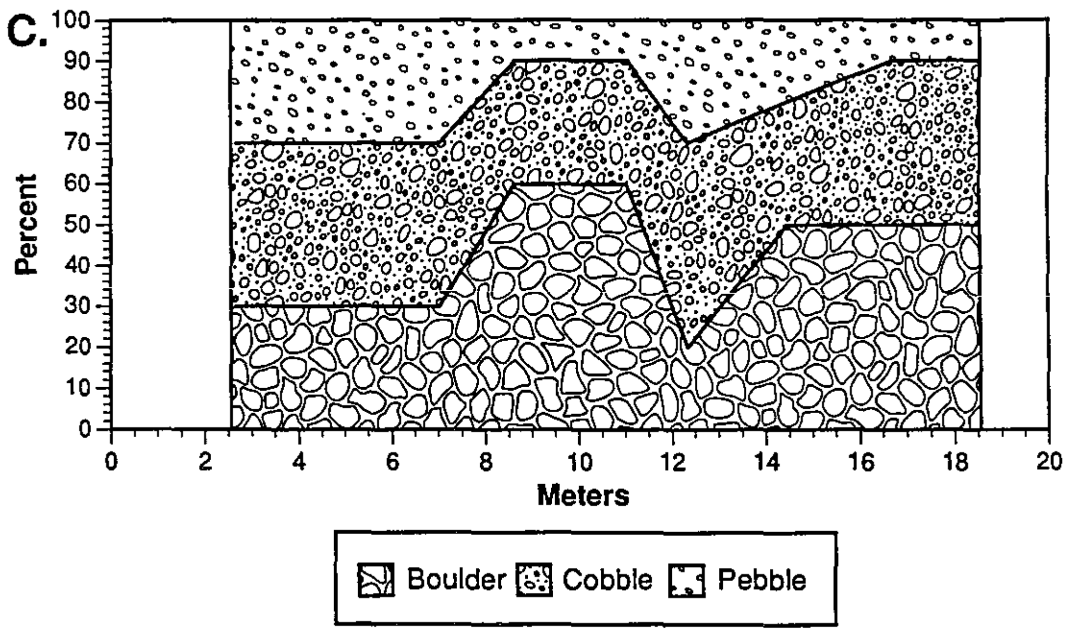
FIGURE 108. Station N-6 on 31 May 1990.

A. Beach sketch. The profile was run down a small draw between two bedrock highs. Note barnacle and mussel zones on lower half of the rock face.

B. Topographic profile, illustrating the steepness of the profile.

C. Surface sediment distribution pattern based on grain size estimates at 8 of the survey points along the profile (circles shown in B). Note slight increase in size down the slope. This surficial debris is angular and poorly sorted, which indicates little transport by wave action.


B.
Rebar
N-6 27 May 90
Bay of Isles
60% AP & CT
A
B
C
A, B, C, =Trenches
WL
1512
cm
0
-100
-200
-300
-400
0
2
4
6
8
10
12
14
16
18
20
Meters


C.
Percent
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
Meters
Boulder
Cobble
Pebble

study. All of the trenches were quite shallow because of the proximity of the bedrock surface, as shown by the photograph in Figure 109B.

Oil Distribution Patterns. The surface oil coverage over time is shown in Figure 110. There was no change in the extent of surface oil through at least January 1990 and probably through spring. The oil occurred as a band of 40-70 percent coverage of black oil on the bedrock and sediments. Oil penetrated and pooled into the crevices and accumulation of sediments on the irregular bedrock surface. The deepest of these crevices was about 30 cm, and a sample collected from 20-30 cm in October contained 780 ppm TPH. The oil on the bedrock surface was dry and weathered, but the oil in the crevices, on the undersides of cobbles and pebbles, and with depth was soft and sticky (Fig. 109B). Even as of 4 September 1990, the oil in crevices had not hardened or formed a pavement-type deposit. Although the surface appeared much cleaner (Fig. 110), 75 percent of the undersides of the sediments were still covered. This more sheltered oil will persist for very long periods because of the very sheltered nature of the site. Although the depth of penetration is limited to the top few centimeters in most areas, the amount of oil can be very high—the September 1990 samples collected at 1-5 cm depth contained 18,540 to 41,240 ppm TPH. Samples from bedrock that had been treated generally had less oil in the crevices (such as N-10, which had 1,000-3,000 ppm TPH in similar samples collected in September 1990). Desiccation, photo-oxidation, and flaking processes have removed much of the oil from the exposed, horizontal surfaces within two summer seasons. The remaining oil is sheltered from these processes and we predict it will persist for many years. However, these oil deposits should become less mobile and biologically available over time as the oil surface forms a weathered skin and eventually becomes a tar deposit.

FIGURE 109. (Facing Page) Photographs of station N-6.

A. Near vertical aerial on 31 May 1990. Location of survey line is shown. Photo by M. Hayes.

B. Trench C on 31 May 1990. See profile in Figure 108B for location. Oil was still soft. Photo by D. Noe.

A.

B.

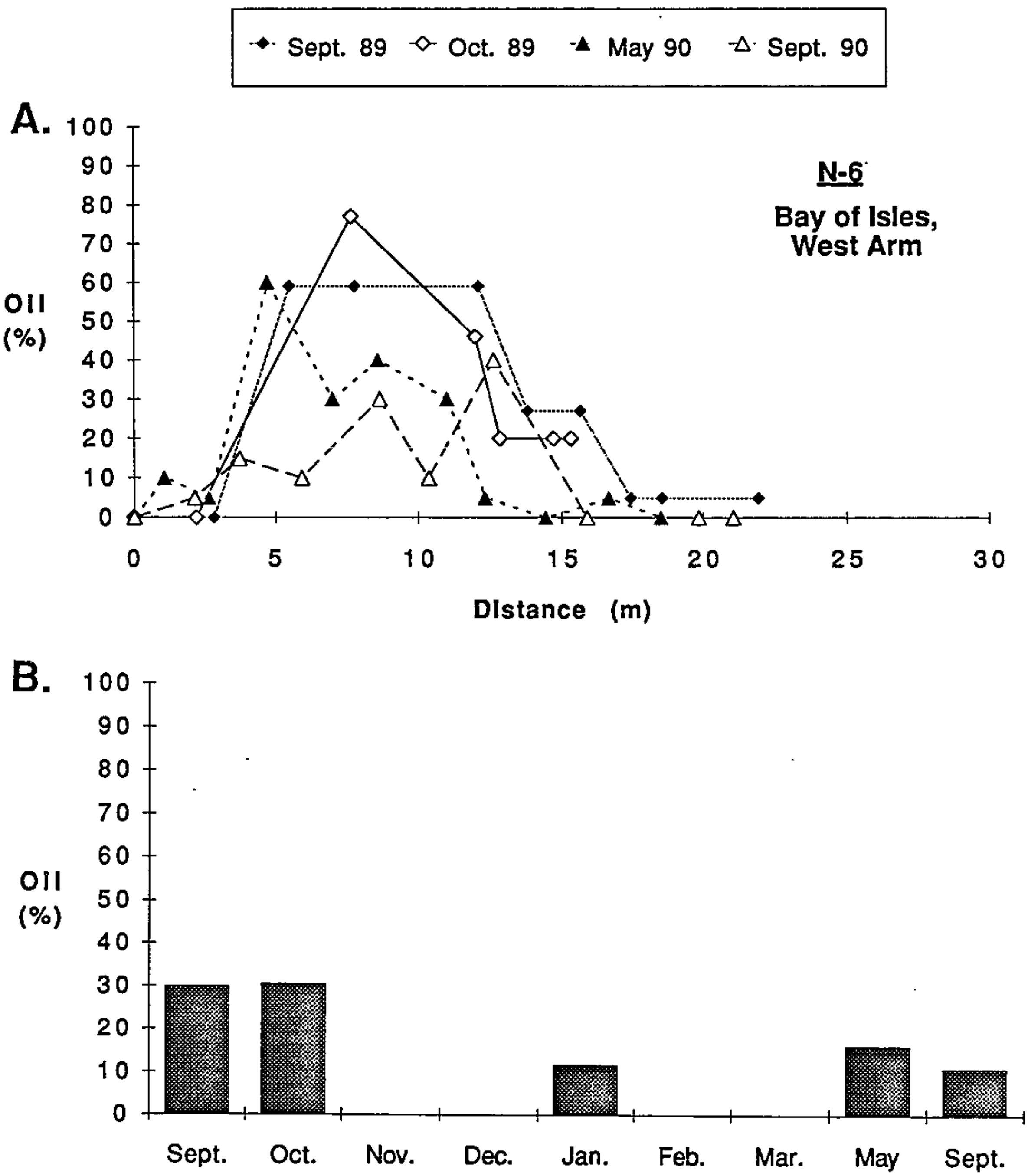


FIGURE 110. Surface oil coverage at N-6 in Bay of Isles.

A. Plot of the surface oil coverage for selected surveys. This station is located on a set-aside. Although the surface oil decreased in 1990, the undersides of cobbles remained 75 percent covered with oil.

B. Surface oil coverage, integrated over the entire profile, for each month.

Observations on Biota. It should be noted that the NOAA biological monitoring station in the Bay of Isles is located west of N-6, in a very different setting. There is no bedrock outcrop and the surface is composed of a hard-packed substrate covered with boulders and cobbles. The lower part of the shoreline is relatively flat and featureless. The site was originally mapped as being lightly oiled in the mid-to-upper intertidal zone, and the June 1990 SSAT survey found only scattered tarballs in the area. Futhermore, the upper zone was treated in 1990 with tilling and bioremediation because the site was just west of the set-aside signs erected by Exxon.

Station N-16

Introduction. The profile at this station was run down a shallow draw through a complex set of bedrock outcrops (Fig. 111A) about one third of the way from the southwest end of the southeast facing flank of Applegate Island (Fig. 16). This side of the island has an open effective fetch in an easterly direction of 29 km (45° angle with trend of island). It is a little less than 3 km directly across the entrance of Port Nellie Juan (toward the southeast). Therefore, there is a potential for considerable wave action at this site, but much of the wave energy is expended on the rocks offshore. The presence of an uplifted, flat wave-cut platform behind the station is further evidence of the potential for wave action in this area. The sediment cover along the profile is thin, but the pebbles that are present are generally well rounded and well sorted, another indication of wave activity. The site is very representative of the shoreline of Applegate Island. This station was in the flexure zone between uplift and downwarp during the 1964 earthquake, therefore it was not subjected to any vertical change, the only one of the permanent study sites that was not uplifted. A field sketch, beach profile, and surface sediment distribution plot for this station on 22 June 1990 are given in Figure 111, and two photographs of the site are presented in Figure 112.

The shoreline was moderately oiled, and the 1989 treatment consisted mostly of manual removal and bioremediation with Inipol. Whether hot-water flushing was used on this specific site is unknown, but it did not look as if the sediments had been disturbed during the limited visit to this site in September 1989. No treatment was conducted at the site in 1990, as far as we know.

N-16 22 June 90
Applegate Island

A.

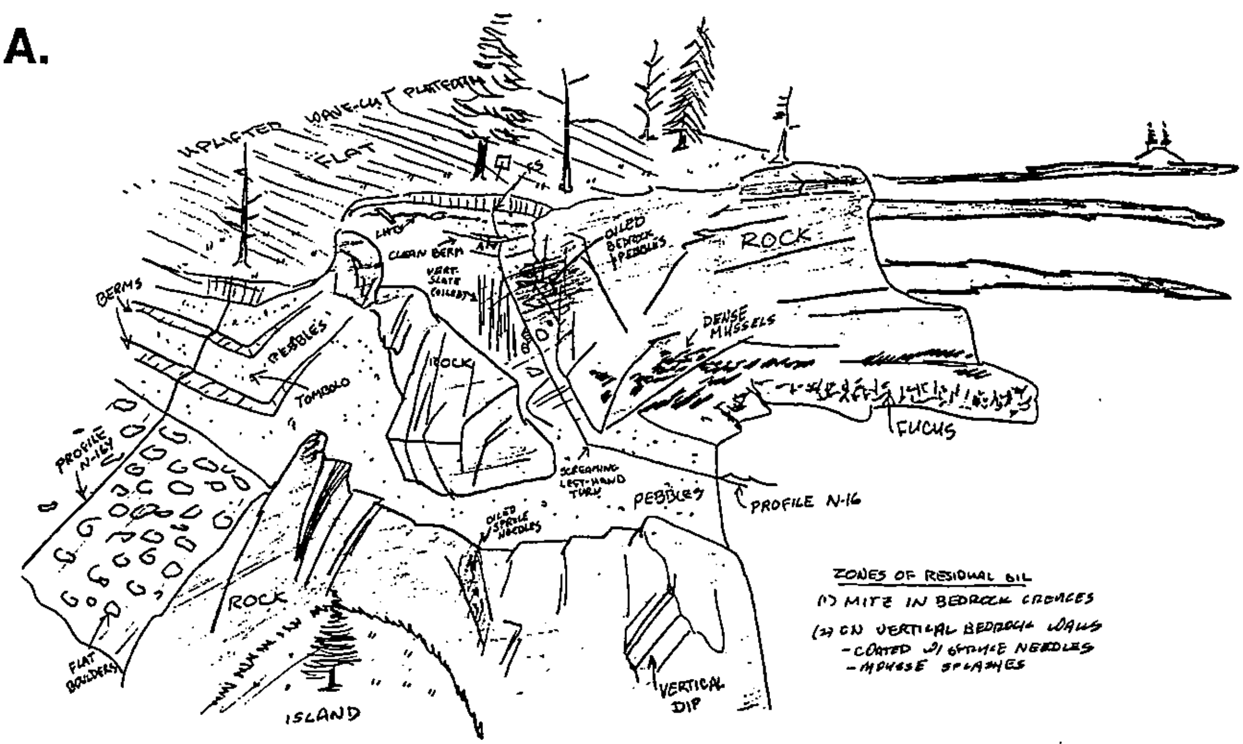


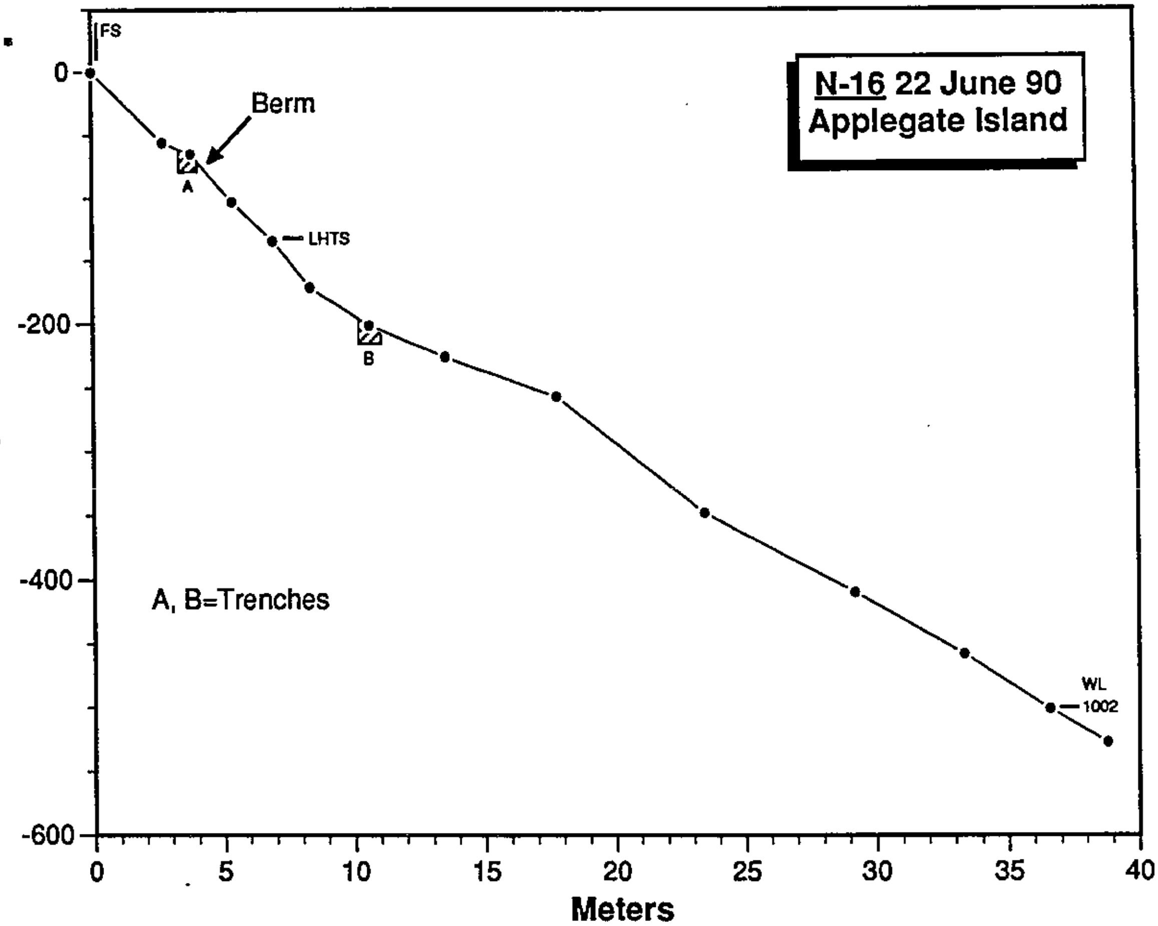
FIGURE 111. Station N-16 on 22 June 1990.

A. Field sketch. The profile was run along a somewhat sheltered draw behind a large outcrop of vertically dipping slate. Note heavy Fucus (popweed) and Mytilus edulis (mussel) growth on the lower portions of the outcrop.

B. Topographic profile of the surface down the draw.

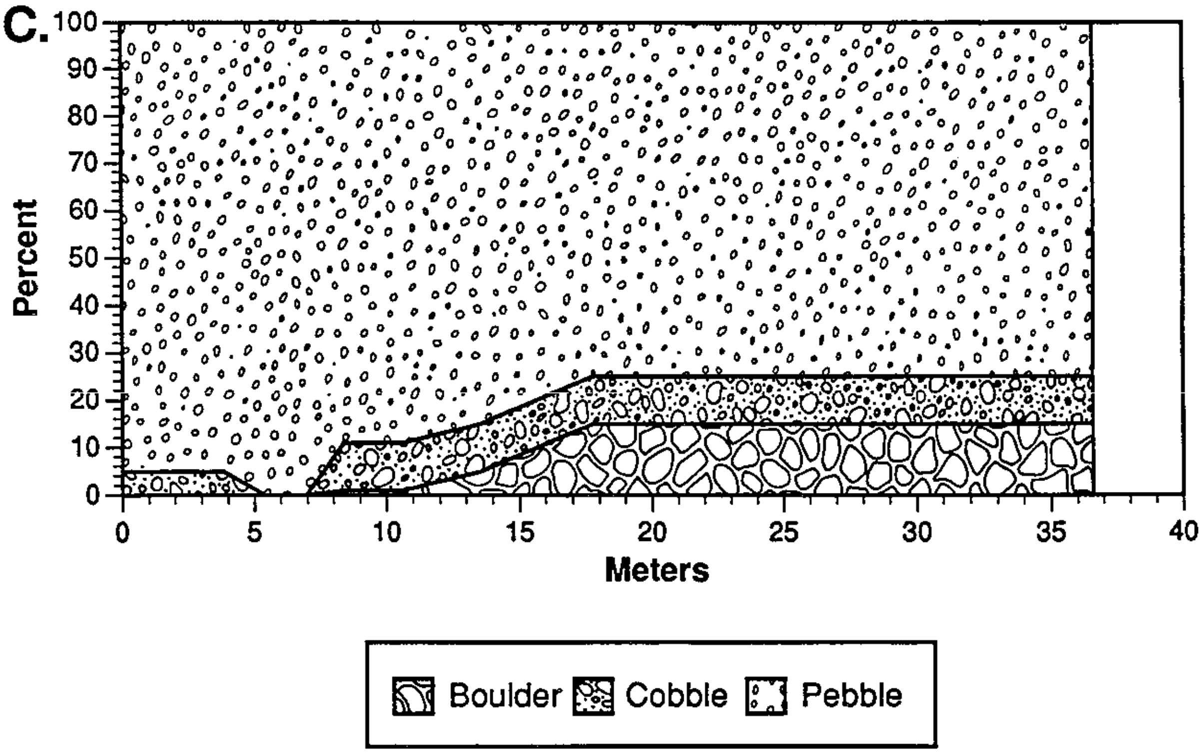
C. Surface sediment distribution along the profile based on visual estimates at 12 survey sites (circles on profile in B). Pebbles predominate throughout the profile.

B.



N-16 22 June 90
Applegate Island
Berm
FS
A
B
LHTS
WL
1002
A, B=Trenches
cm
0
-200
-400
-600
0
5
10
15
20
25
30
35
40
Meters

C.



Percent
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Meters
Boulder
Cobble
Pebble

Morphology and Beach Dynamics. The beach profile surveyed at this site, which is presented in Figure 111B, is a simple offshore slope down the draw surface. The profile line surveyed was chosen to avoid profiling over the bedrock, a decision which necessitated a sharp left turn of the profile near low water. This profile was run five times during the study. Except in the area of the high-level berm, there is no chance for significant change on this profile over a one year period because it is essentially a bedrock surface covered by a thin veneer of sediments. The potential for a vertical sediment envelope of a few tens of centimeters does exist for the high-tide pebble berm. As can be seen in the field sketch (Fig. 111A), a well-developed pebble tombolo has formed a few meters to the southwest of the profile on a higher, more exposed point.

Sediments. The sediments along the profile were derived from the local bedrock outcrops, which are composed of vertically-dipping, crumbly dark-colored slate. As shown in Figure 111C, the surface sediment is more than 70 percent pebbles throughout. Cobbles and boulders make up roughly 25 percent of the surface material on the lower half of the profile. The clasts are very flat and thin, reflecting their source, the thinly bedded slate. A total of 15 trenches were dug at this site during the study. The trenches were usually less than 40 cm deep, bottoming out in bedrock and, for the most part, penetrating only pebbles.

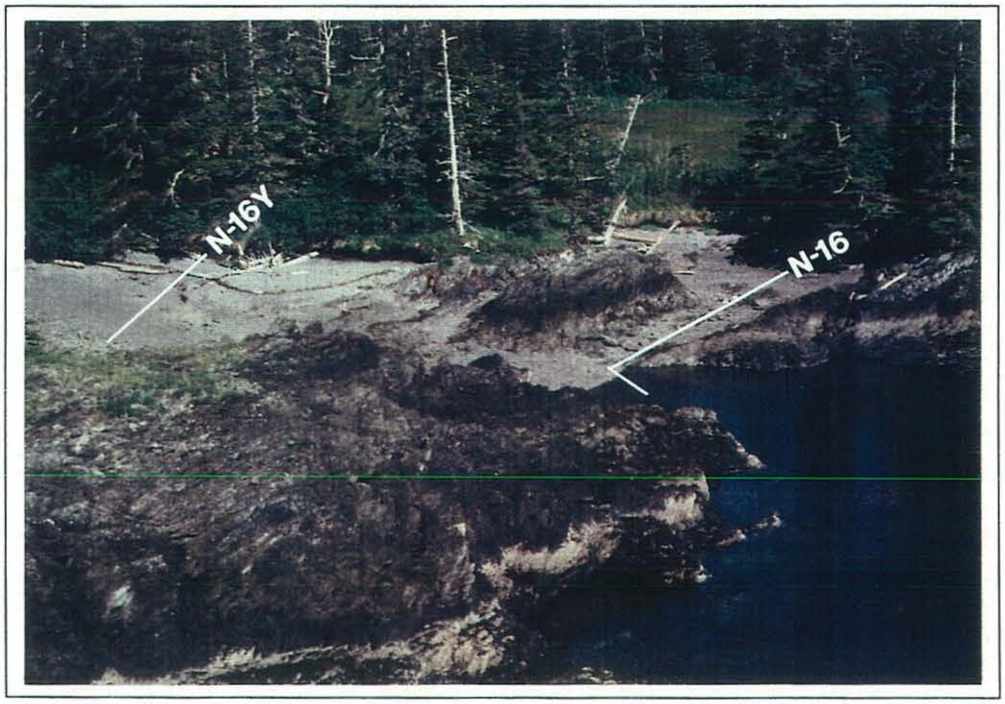
Oil Distribution Patterns. The surface oil distribution over time at N-16 is shown in Figure 113. The oil has three distinctive distributions. The pebble berm at the high-tide line, which was heavily oiled in September 1989, contained only 5 percent surface oil in November and 20 percent in December. Sediment reworking during the October high tides was very evident.

FIGURE 112. (Facing Page) Photographs of station N-16.

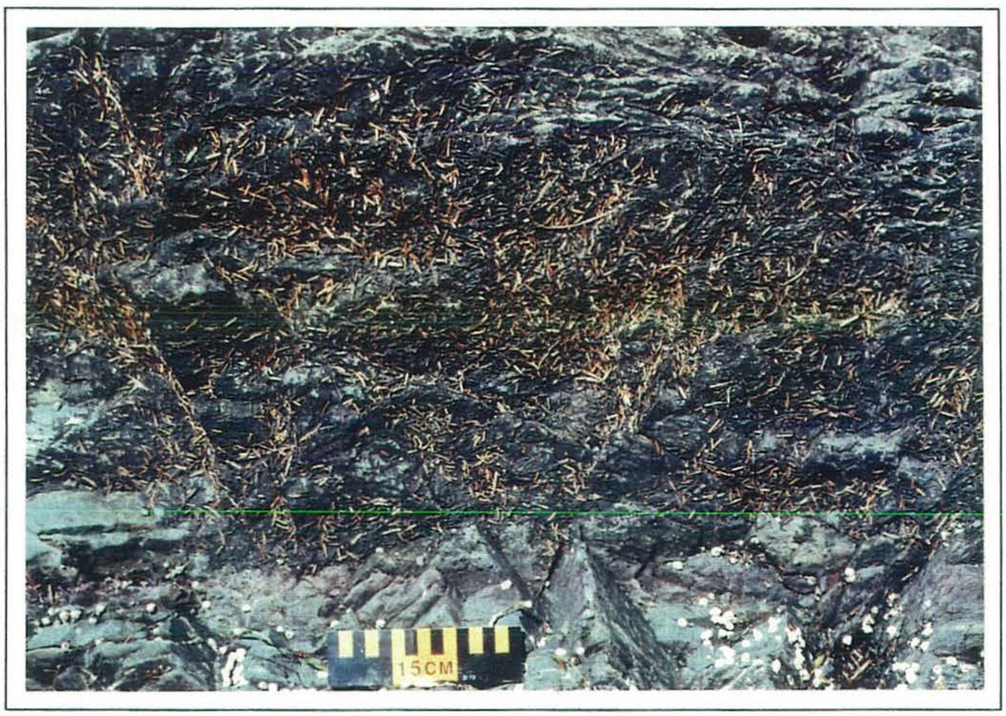
A. Oblique aerial view on 22 June 1990. Locations of both profiles N-16 and N-16Y are given. Surface sediments are clean. Photo by M. Hayes.

B. Spruce needles adhering to oiled rock surface near mid-tide level. The presence of spruce needles like this was frequently used to differentiate between black lichens and oil during shoreline surveys. Photo by J. Michel.

A.



B.



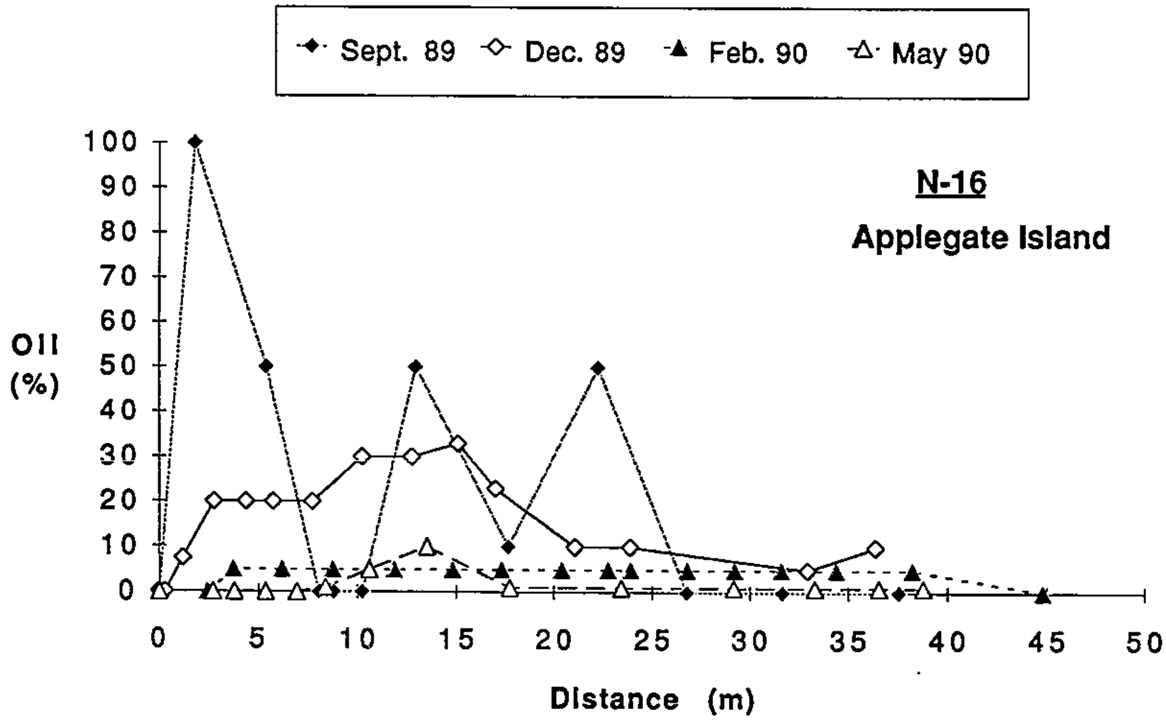


FIGURE 113. Distribution of surface oil coverage for selected surveys at N-16 on Applegate Island.

The oil zone at 10-15 m on the profile represents the oiled bedrock which is sporadically covered by clean pebbles. The oil, which is a soft, brown mousse, has filled the crevices created by the upturned, thin beds of slate. Even though the pebbles move back and forth over the bedrock surface, the mousse is well-imbedded into the crevices and showed no evidence of being removed over time.

The third type of oiling in September 1989 was a heavy coating of brown mousse on the underside of the larger cobbles scattered about at random. This oil was very thick and sticky. By the next survey in November, this oil was gone, and it was never observed again.

There seemed to be no erosion or accumulation of sediments in this bedrock pocket, and only reworking of the surface sediments. After September 1989, the surface was relatively clean, but, oil persisted at depth. Table 21 shows the results of chemical analysis of sediments from this profile. Only subsurface sediments are shown, and all samples were collected at the contact between the pebble berm and the bedrock—this depth ranged from 20-25 cm at the pebble berm crest and to 10-15 cm at the mid-tide zone. This pocket beach did not get really reworked to bedrock until after the December 1989 survey. The late December/early January storms apparently mobilized the pebble berm, and both visual and quantitative measures of oil dropped. However, oil persisted at this protected pocket beach as late as June 1990. The trench descriptions note 10-20 percent mousse coverage on the pebbles with depth.

TABLE 21. Sediment TPH (in ppm) for N-16 on Applegate Island by morphological zone.

Subsurface Samples		
Date	Pebble Berm	Mid-Tide Zone
9/89	950/1,600	
11/89		140
12/89	4,180	
2/90	320	20

GEOMORPHOLOGICAL CONTROL STATIONS

In order to cover what we consider to be the full spectrum of gravel beach types in the vicinity of PWS, we studied two additional sites, in June 1990. Station PB-1, which was chosen to represent the highest extreme of wave energy available in the area, is located on the outer coast of Montague Island (Fig. 16.). Station N-16Y, on the other hand, is located in an area of much lower wave energy, the east shore of Applegate Island (Fig. 16). Even so, N-16Y maintains the standard cobble/boulder platform with berms configuration. The effective fetch of PB-1 is infinite, and that of N-16Y is <15 km.

The morphology of station PB-1 is illustrated by the field sketch, topographic profile, and surface sediment distribution plot of Figure 114 and by the two photographs in Figure 115. This area was subject to over 3 m of uplift during the 1964 earthquake, but the consistent, large waves of the area, some of the largest in the world, have rapidly established a beach similar to those in the highly exposed areas unaffected by the uplift. Note the large, multiple gravel berms at the upper part of the profile and the eroded wave-cut platform of the lower part (Figs. 114 and 115). This profile is characteristic of highly exposed gravel beaches on tectonically active coasts that are undergoing long-term retreat. The raised platform has obviously been carved by wave action over the past 26 years. During major storms, the highest berm (storm berm) is built higher as the shoreline retreats. The lower-level berms on the face of the storm berm accrete during intervals between the storms. The wave-cut platform is overlain by an armor of boulders that average 60-100 cm in diameter. The grain size distribution pattern given in Figure 114C shows that the very coarsest material occurs on the outer platform, and somewhat finer material occurs on the depositional berms, with the storm berm being slightly coarser than the lower-level berms accreted on its seaward face.

The detailed description of the gravel beach exposed to much smaller waves, station N-16Y, is given in Figure 116. Note the small berms at the high-tide level. Also note the grain-size distribution (Fig. 116C), which is similar to the one on the highly exposed beach (Fig. 114C), with boulders on the uplifted platform and smaller material on the depositional berms, which indicates the importance of the wave-sorting process at the site. Except for the lower platform of PB-1, which is nearly flat, the slopes on these two beaches are remarkably similar. The beachface slope is between 11-12° (on the average) at both sites and the upper platform slopes 5° at both sites.

PB-1 24 June 90
Montague Island

A.

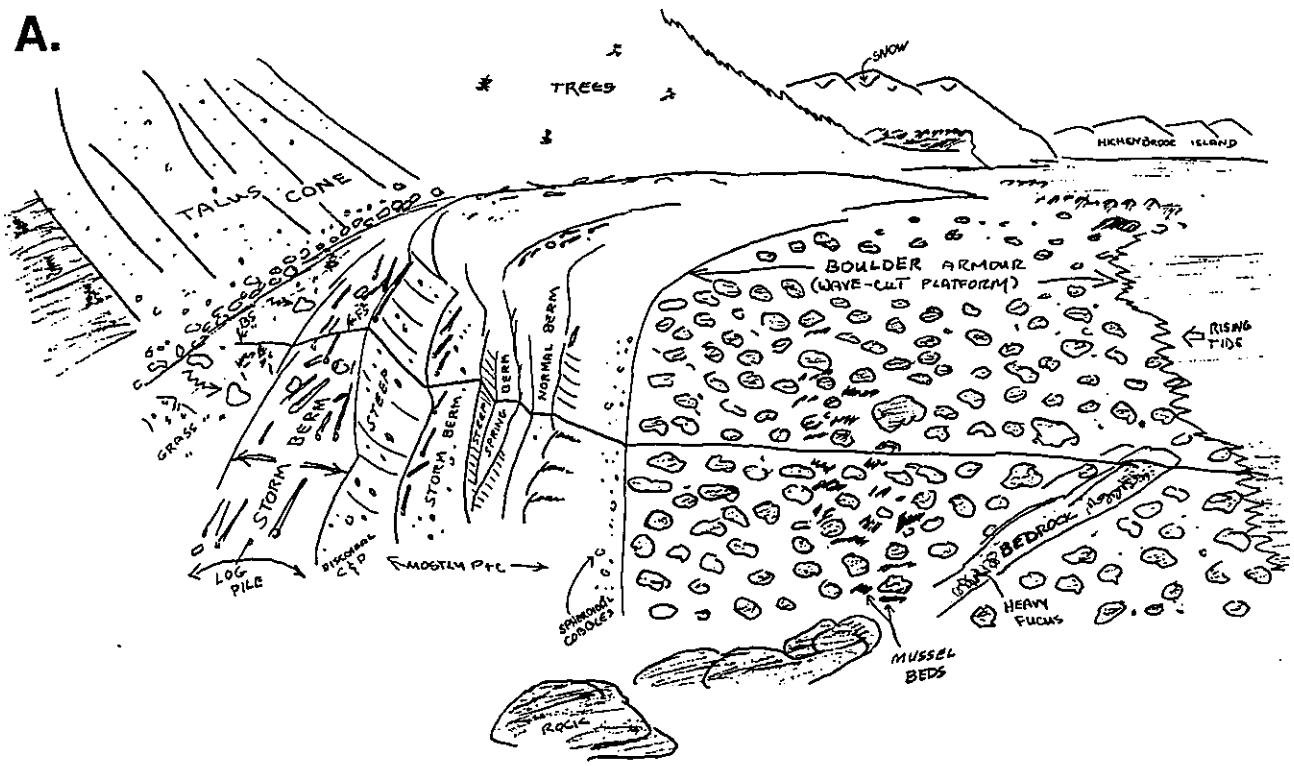
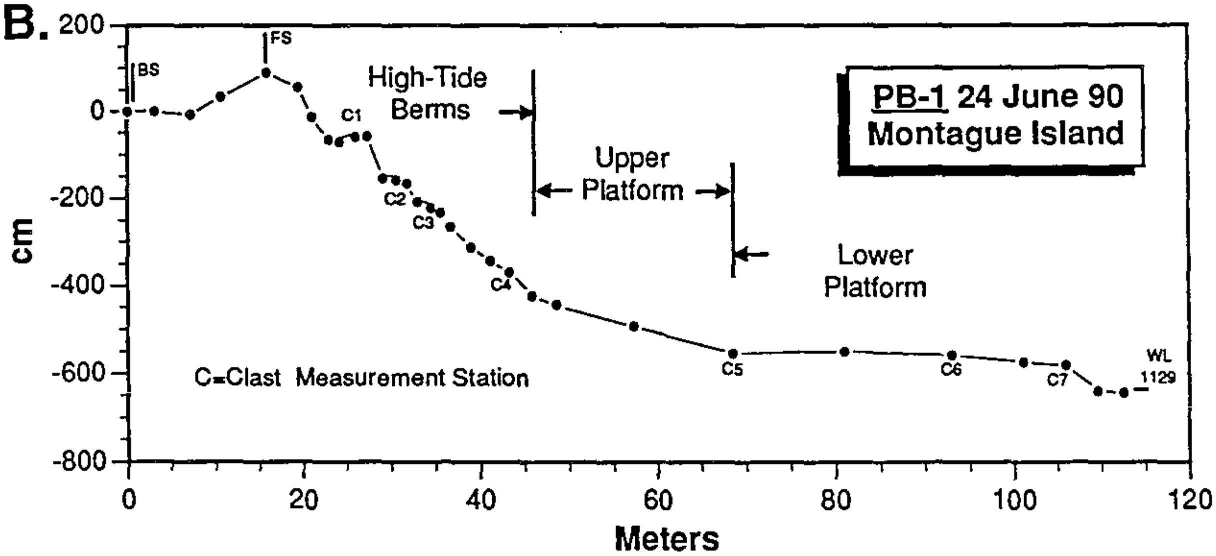


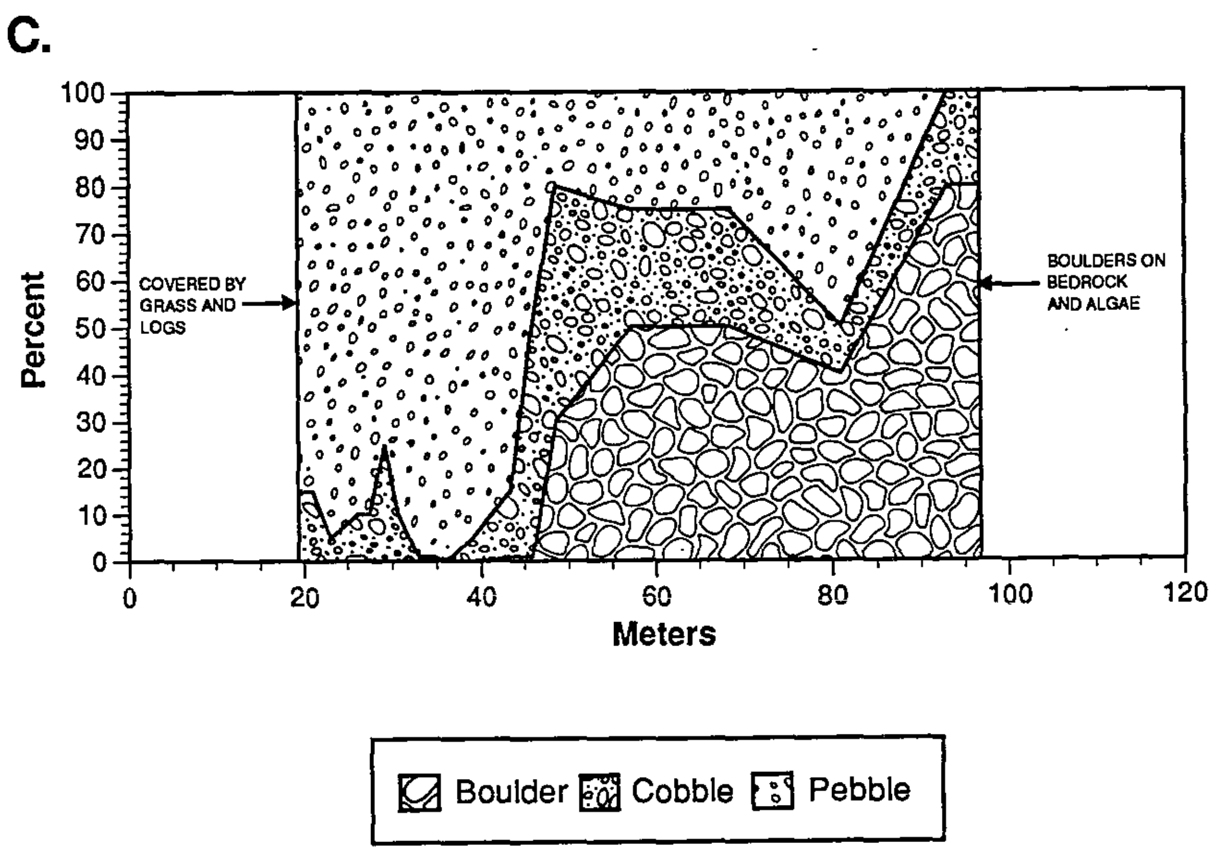
FIGURE 114. Station PB-1 (outer Montague Island) on 24 June 1990.

A. Field sketch. This profile is typical of exposed, high-energy beaches in an eroding, retreating setting. Though subject to more than 3 m of uplift in the 1964 earthquake, the beach has readjusted to its previous configuration because of the constant reworking of the beach by large waves.

B. Topographic profile illustrating the three major components of the beach—a complex set of high-tide berms, a moderately sloping upper platform, and a nearly flat lower platform.

C. Distribution of surface sediments along the profile, based on estimates made at each of the survey sites (circles on diagram B). Note offshore coarsening trend. The platform is highly armored.


B.
cm
Meters
BS
FS
C1
C2
C3
C4
C5
C6
C7
High-Tide Berms
Upper Platform
Lower Platform
PB-1 24 June 90
Montague Island
C=Clast Measurement Station
WL 1129


C.
Percent
Meters
COVERED BY GRASS AND LOGS
BOULDERS ON BEDROCK AND ALGAE
Boulder
Cobble
Pebble

An analysis of these two sites, as well as those described above for the three shoreline types—(1) cobble/boulder platforms with berms; (2) bayhead beaches; and (3) pebble beaches with tidal flats—shows some remarkable differences, with regard to both their morphology and sediments and how they would respond to spilled oil. All of these different types of beaches would be classified as either gravel beaches (ESI=7) or sand and gravel beaches (ESI=6). We still believe their ranking on the ESI Index relative to other environments is accurate, but they show such a wide range of behavior it may be useful to further differentiate them in areas where they are abundant, which would include all of the coast of south-central and southeast Alaska, of course.

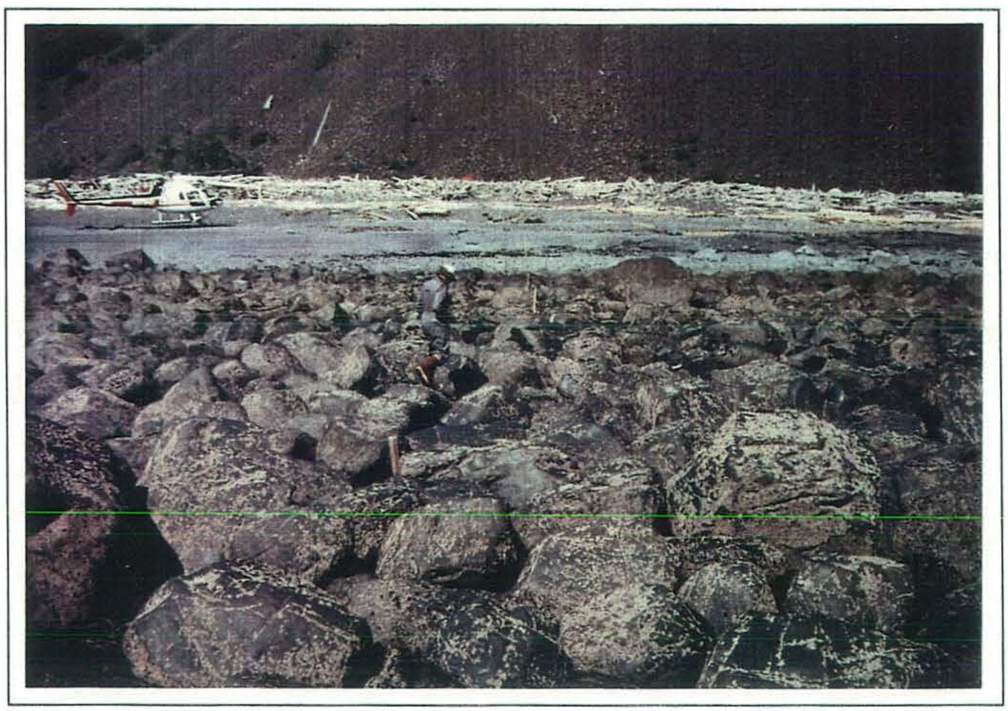
FIGURE 115. (Facing Page) Photos of station PB-1 taken on 24 June 1990.

A. Oblique aerial view looking northwest. Location of profile line is indicated. Photo by M. Hayes.

B. View landward along profile from near the seaward end. The well-armored boulders average around one meter in diameter. Photo by D. Noe.

A.

B.



N-16Y 25 June 90
Applegate Island

A.

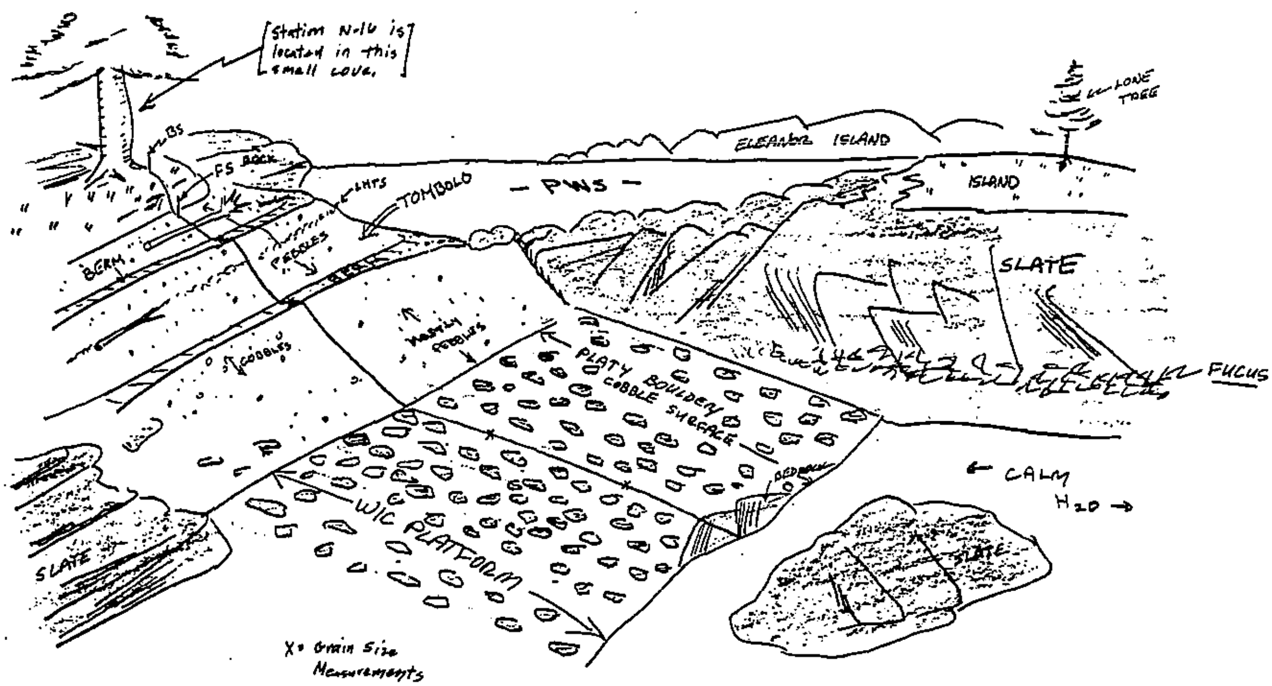


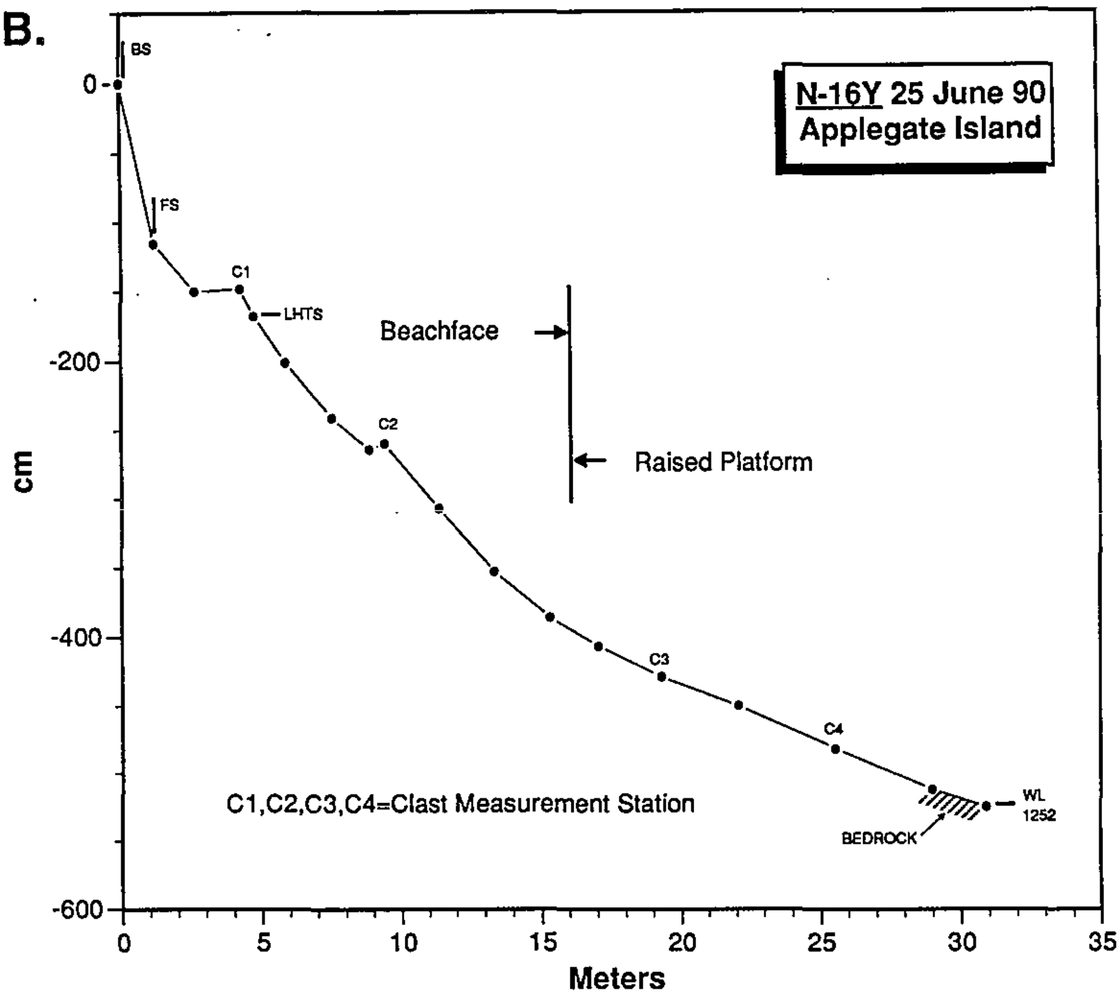
FIGURE 116. Station N-16Y on 24 June 1990.

A. Field sketch. Note the occurrence of subangular boulders on the raised platform and the two high-tide berms.

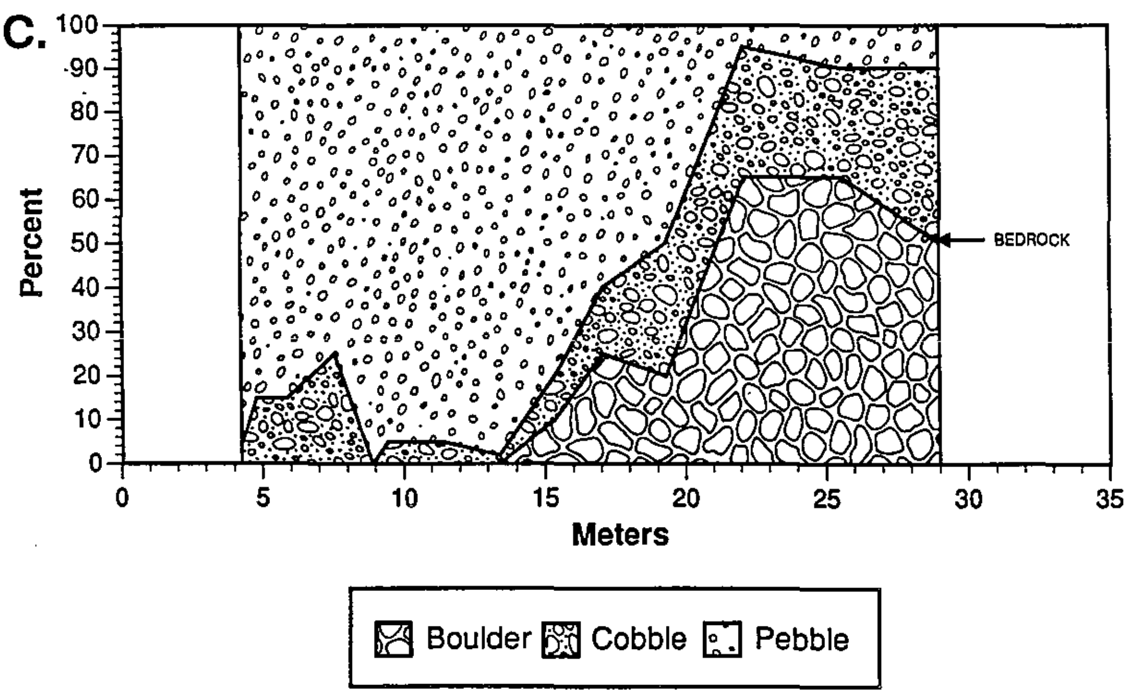
B. Topographic profile, showing clear difference in slope between the two divisions of the beach. Compare with sketch in A.

C. Distribution of surface sediments based on grain-size estimates made at 13 of the survey sites on the profile (circles in B). Similar to station PB-1, the sediments on this station coarsen in an offshore direction.

B.


N-16Y 25 June 90
Applegate Island
BS
FS
C1
LHTS
Beachface
Raised Platform
C2
C3
C4
C1,C2,C3,C4=Clast Measurement Station
BEDROCK
WL
1252
cm
0
-200
-400
-600
0
5
10
15
20
25
30
35
Meters

C.


Percent
100
90
80
70
60
50
40
30
20
10
0
BEDROCK
0
5
10
15
20
25
30
35
Meters
Boulder
Cobble
Pebble

GEOMORPHIC STUDIES IN OUTER KENAI AREA

INTRODUCTION

In order to broaden the scope of our study to include more exposed shorelines, some preliminary studies were carried out in the Outer Kenai Peninsula area. Both authors participated in the spring SSAT survey in the Outer Kenai area in April 1990, and three stations were chosen at that time for detailed study. In May 1990, three stations were established, YG-2, US-5, and PD-1 (see locations on Fig. 17). The results of the work at each of these locations provides a valuable insight into understanding the geomorphological controls of oil spills on gravel beaches.

STATION US-5

This station is located on a north-northeast facing crenulate bay on Ushagat Island in the Barren Islands. It has an effective fetch to the north, the dominate wave approach direction, of about 150 km. Thus, the station is clearly subjected to some very large waves several times per year. A field sketch, beach profile, and surface sediment distribution plot for the station are given in Figure 117 and two photographs of the site are given in Figure 118. Ushagat Island was downwarped about 1 m in the 1964 earthquake.

Hayes visited the site on 22 April 1990, and his SSAT team discovered an oiled layer 80 m long and averaging 10 m wide that was buried 10-25 cm beneath the surface of a high berm near the most sheltered part of the bay (Fig. 118A). The oil/ sediment layer ranged between 8-12 cm in thickness. The layer was still in place and unmodified on 29 May 1990 (Fig. 118B). As can be seen from the beach profile in Figure 117B and photograph in Figure 118A, this is a steep beach with a broad beachface. It is depositional throughout, and most of the beachface is covered by granules. This is a <u>bona fide</u> depositional gravel beach, and the waves that formed it were primarily <u>reflective</u> in character. The buried oil layer, which is clearly shown in the photograph in Figure 118B, was covered over by the normal process of berm accretion. The trench shown in the photograph, as well as the others dug at the site that contained buried oil, are illustrated in Appendix A.

US-5Z 29 May 90
Ushagit Island

A.

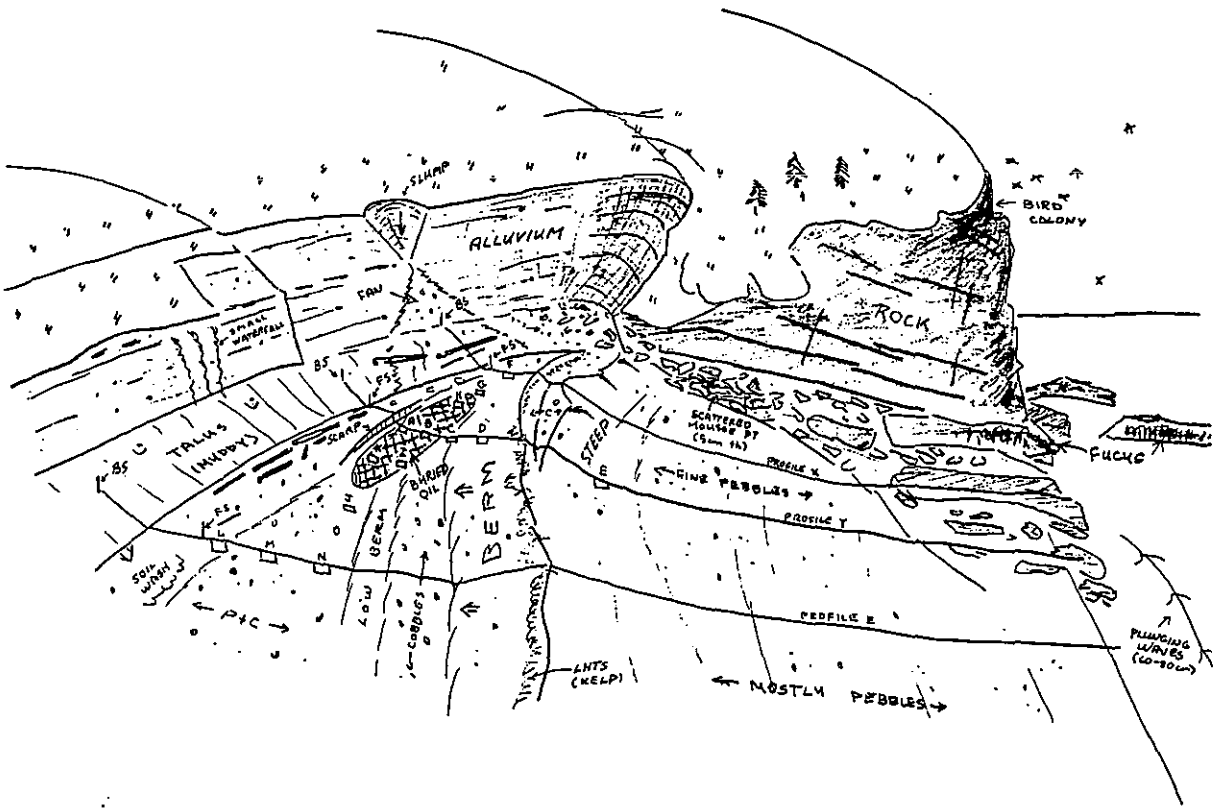


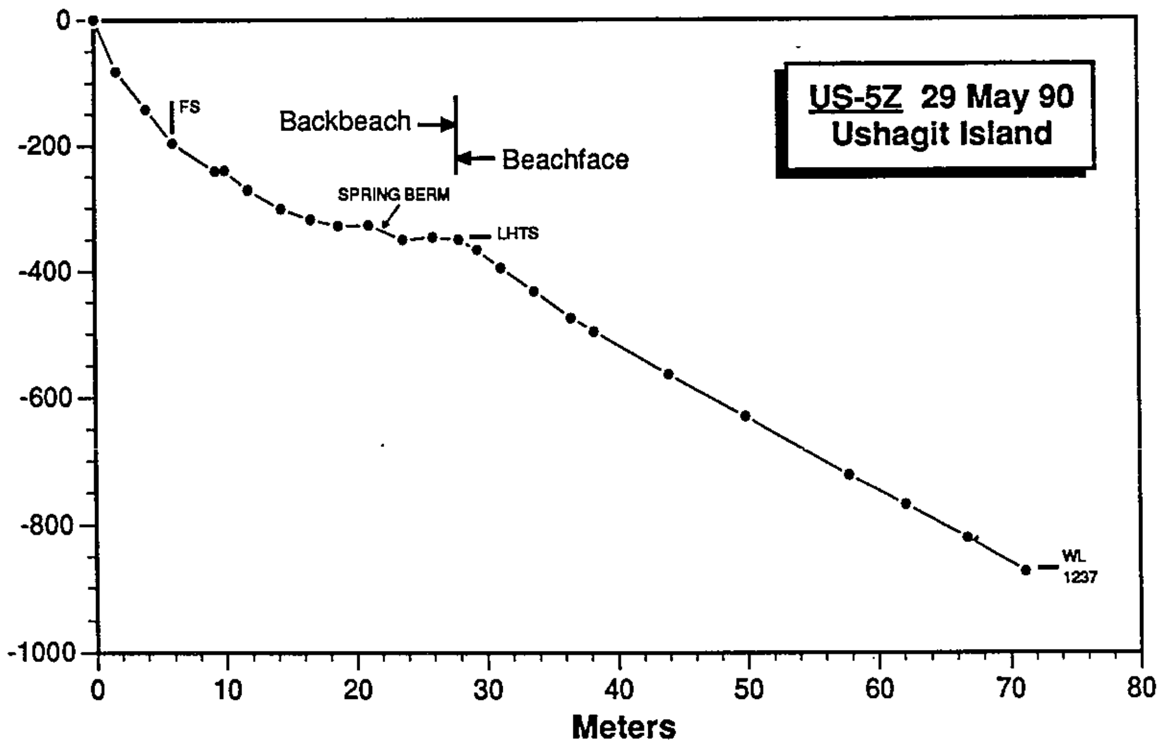
FIGURE 117. Station US-5 on 29 May 1990.

A. Field sketch, showing the area studied on this date. Note location of buried oil.

B. Topographic profile of station US-5Z, the closest profile in the sketch (diagram A). Note the long and continuous beachface, a function of the large waves that mold this beach.

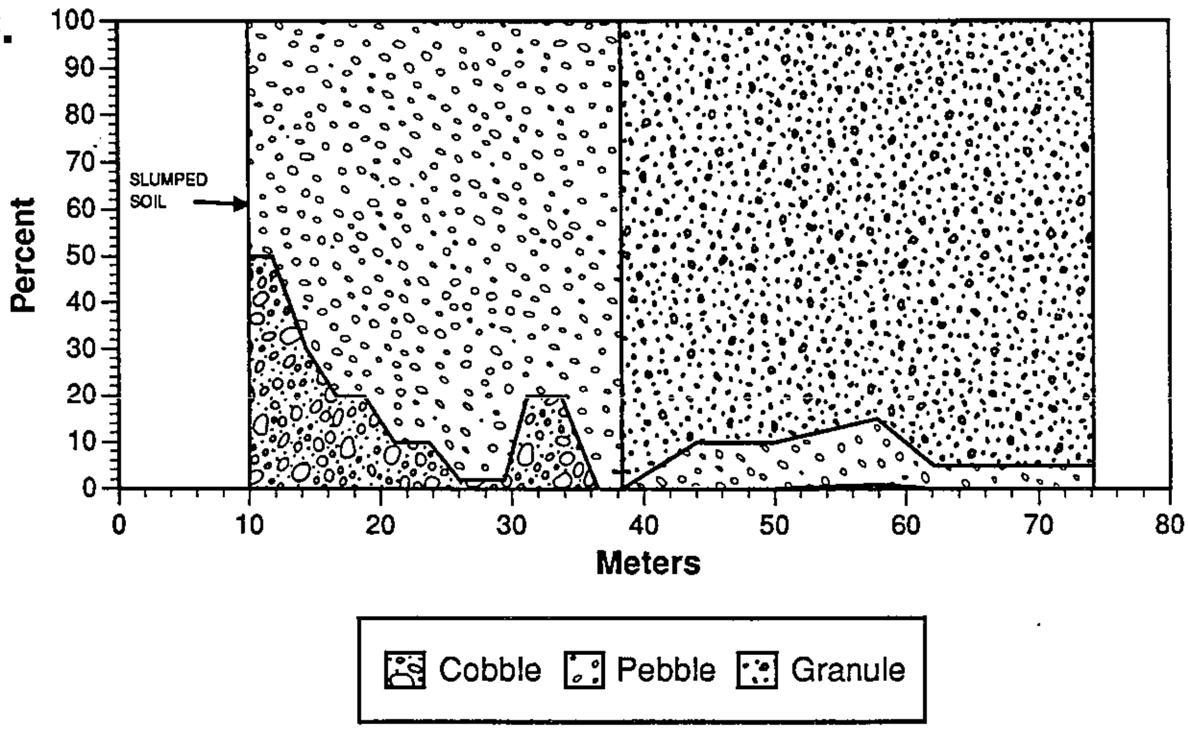
C. Distribution of surface sediments on profile US-5Z, based on visual estimates at the survey points along the profile (circles on diagram B). Note lack of boulders and cobbles on this reflective depositional beach.

B.



US-5Z 29 May 90
Ushagit Island
FS
Backbeach
Beachface
SPRING BERM
LHTS
WL
1237
cm
0
-200
-400
-600
-800
-1000
0
10
20
30
40
50
60
70
80
Meters

C.



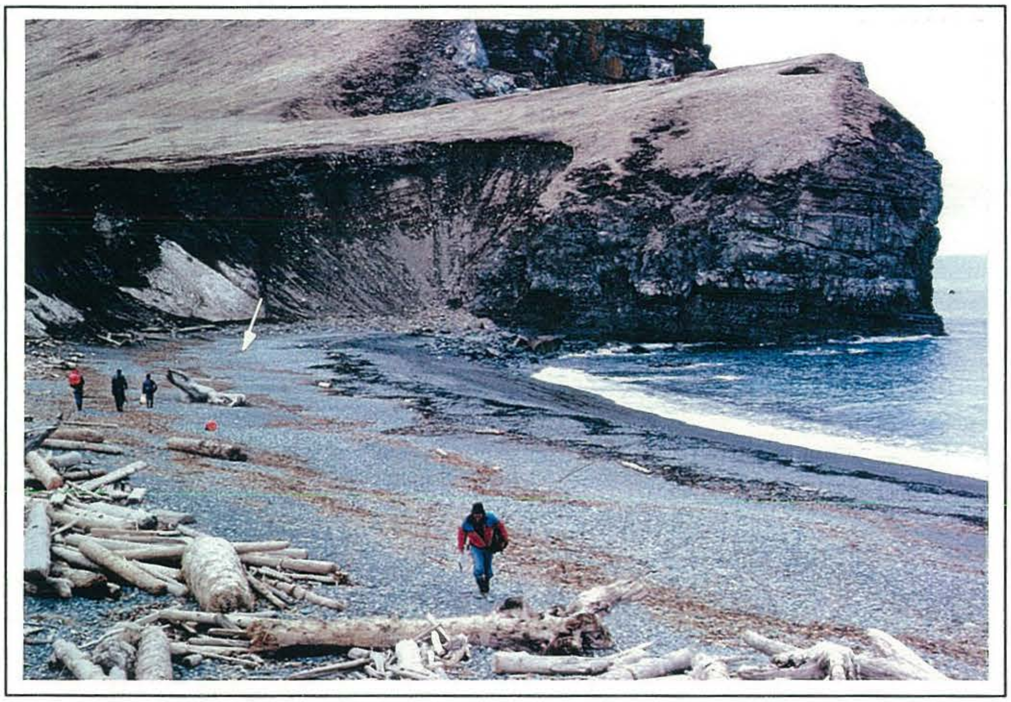
SLUMPED SOIL
Percent
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
Meters
Cobble
Pebble
Granule

FIGURE 118. (Facing Page) Photographs of station US-5.

A. SSAT team on the beach at US-5 on 22 April 1990. View looks northwest. Note eroded crenulate bay. Arrow points to area where buried oil layer was found. Photo by M. Hayes.

B. Buried oil sediment layer in trench H (see sketch in Fig. 117A for location) on 29 May 1990. The 8 cm thick oiled layer was buried beneath 28 cm of clean pebbles and granules. Photo by D. Noe.

A.



B.

STATION YG-2

This station is located on the front of the glacial outwash fan of the Yalik Glacier that sunk around 1.8 m during the 1964 earthquake. As a result of that sinking, a giant swash bar has formed and is slowing migrating landward across the sunken outwash plain. The shoreline faces southwest down a narrow embayment behind Nuka Island. It is about 22 km down this irregular-sided channel to Gore Point. At times, sizeable waves must be generated along this fetch. There is also a narrow passage to the southeast that reaches Nuka Bay, but, again, the local topography is complex. A detailed zonal study was carried out at this site on 30 May 1990. The intertidal zone is dominated by the huge swash bar, which has a slip face 90 cm high. Both plan-view and oblique-view field sketches of the site are given in Figure 119, a beach profile and surface sediment distribution plot are given in Figure 120, and two photographs are shown in Figure 121.

Hayes visited this site with his SSAT team on 28 April 1990, over one year after the spill. At that time, an asphalt pavement over 1 km long and averaging ± 10 m in width was present near the mean high-tide line on the seaward side of the bar. Pieces of the asphalt pavement had been eroded and transported across the bar crest, creating the potential for burial when the bar moves further landward.

When our field team visited this site on 30 May 1990, we found the asphalt pavement, the largest one at the EXXON VALDEZ spill site (to our knowledge), to be little changed. The pavement averaged 8-10 cm thick. It was manually removed from the site in the summer of 1990 and transported to a landfill in Oregon.

It is probable that, because of its unique setting in a submerged glaciated valley sheltered from wave attack, the beach at Yalik Glacier is never subjected to anything but dissipative wave conditions. This beach, which is primarily a slowly moving swash bar with a cap of asphalt pavement, is a study in contrast to the exposed, reflective beaches of the Barren Islands, where the burial of oil under depositional berms was the dominant theme.

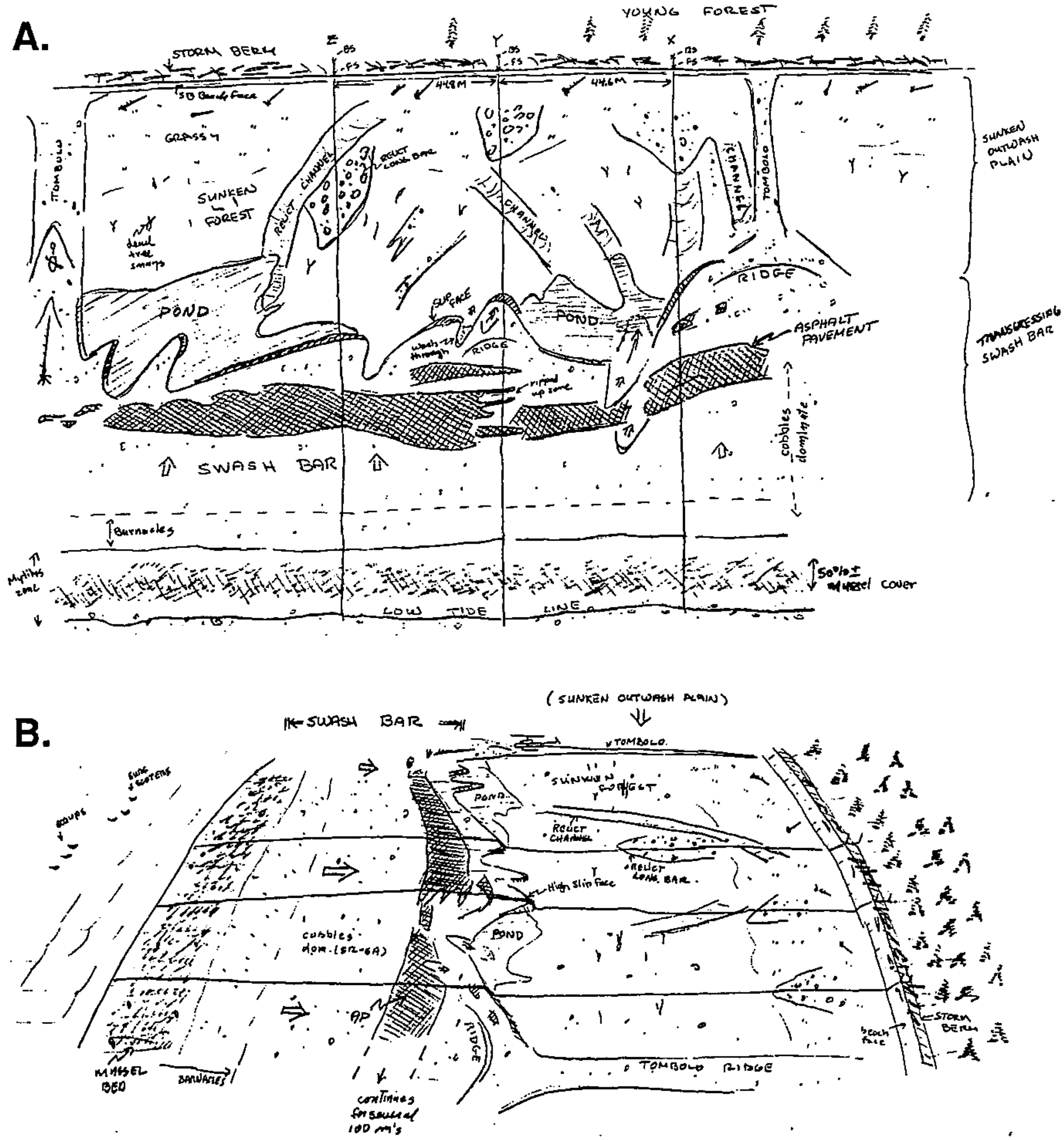


FIGURE 119. Field sketches of station YG-2 on 30 May 1990.

A. Plan view. There are 3 primary features of this site—(1) a continuous storm berm at the spring-high-tide level; (2) the sunken surface of the former glacial outwash plain; and (3) the landward migrating swash bar. Note the extensive asphalt pavement. The distance between profiles X and Z is roughly 90 m.

B. Oblique view, looking northwest.

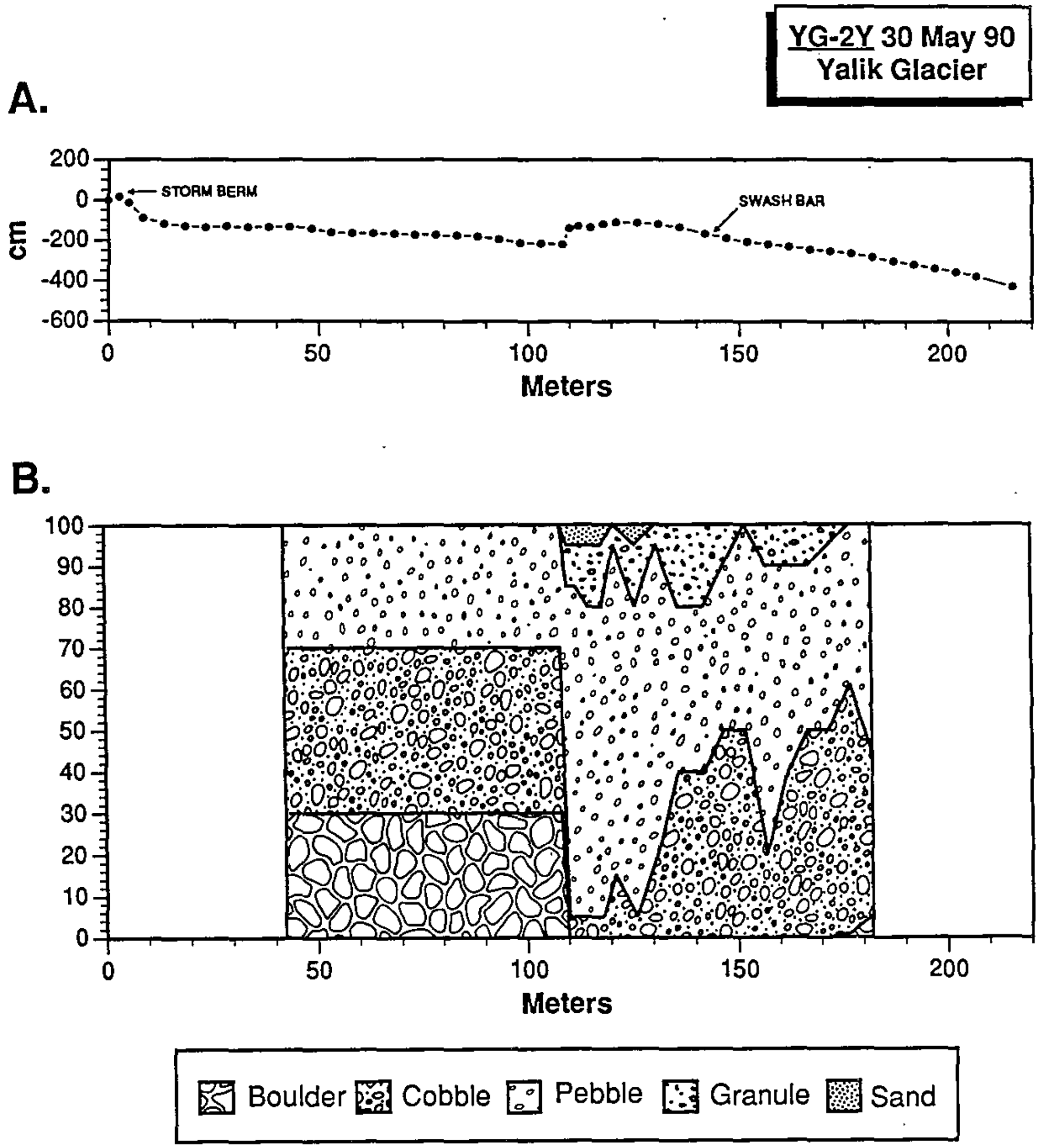


FIGURE 120. Station YG-2Y ON 30 May 1990.

A. Topographic profile for station YG-2Y (see sketch in Fig. 119A for location). The swash bar is the dominant feature on the beach.

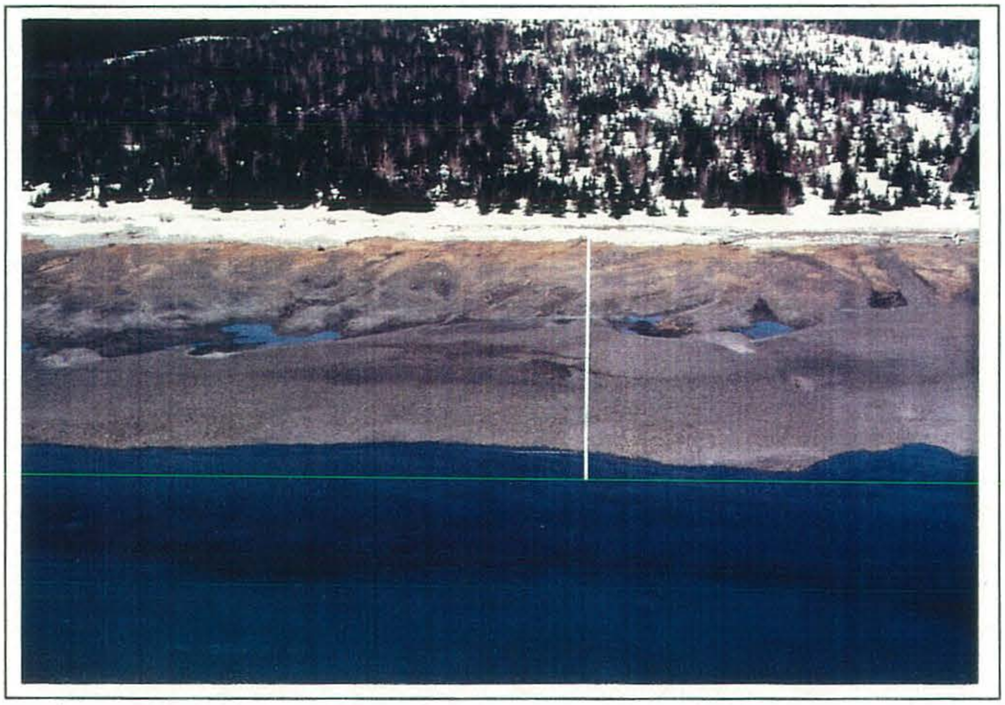
B. Distribution of surface sediments based on visual estimates at each survey site (circles on plot in diagram A). The sediments landward of the swash bar were deposited on gravel bars on the sunken outwash stream. Note slight increase in grain size down the offshore side of the swash bar.

FIGURE 121. (Facing Page) Photographs of station YG-2 on 28 April 1990.

A. Oblique aerial view looking northeast (landward). Compare with sketch in Figure 119A. The tide was considerably higher when this photograph was taken than when the sketch in Figure 119A was drawn. The location of profile YG-2Y is indicated. Photo by M. Hayes.

B. Ground view looking northwest along the surface of the asphalt pavement. Photo by M. Hayes.

A.



B.

STATION PD-1

This station is located near the head of Port Dick on the north shore (Fig. 17). It faces south directly across the channel, a distance of less than 2 km. It is about 15 km in an east-southeasterly direction down the Port Dick west channel to the entrance. It is likely that major storms with a southeasterly wind component generate large waves in Port Dick, but they would approach the beach at a 70-90° angle. This area was downwarped about 1.5 m during the 1964 earthquake. A field sketch, topographic profile, and surface sediment distribution plot are given in Figure 122.

As indicated in the sketch in Figure 122A, this station is located in the lee (downdrift) of a protuberance of sediment that is slowly moving toward the head of Port Dick. We observed an asphalt pavement being slowly buried by this process.

The beach profile has three components:

1) Pebble berm

   This small berm is composed of angular pebbles, indicating sporadic transport. The berm is perched on a bedrock surface.

2) Beachface terrace

   A smooth, relatively steeply sloping (13°) surface with a superb armor of coarse, angular to subangular pebbles. The sediment veneer is underlain by a sunken soil horizon.

3) Platform

   The platform slopes offshore at a much smaller angle (6°), and it, too, has a soil-like substance under the sediment veneer. A well-developed cobble armor is present. An asphalt pavement was located just east of the profile (Fig. 122A). The coarsest sediments on the beach (50 percent cobbles) occur in this zone (Fig. 122C).

This beach is morphologically similar to the cobble/boulder platforms with berms in PWS. The sediments are finer and the waves are smaller, however. Another major difference is the migrating beach protuberance, a feature we did not see in PWS. Because of the shallow soil zone, oil penetration was not a problem in this location. The asphalt pavement was removed manually in the summer of 1990.

PD1 30 May 90
Port Dick

A.

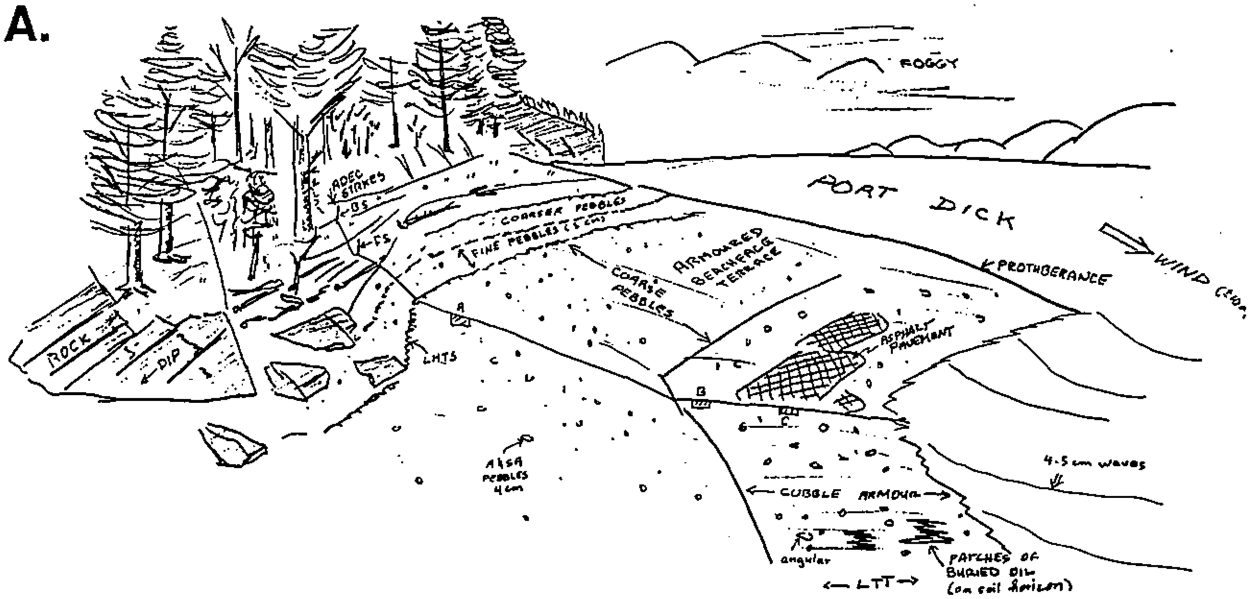
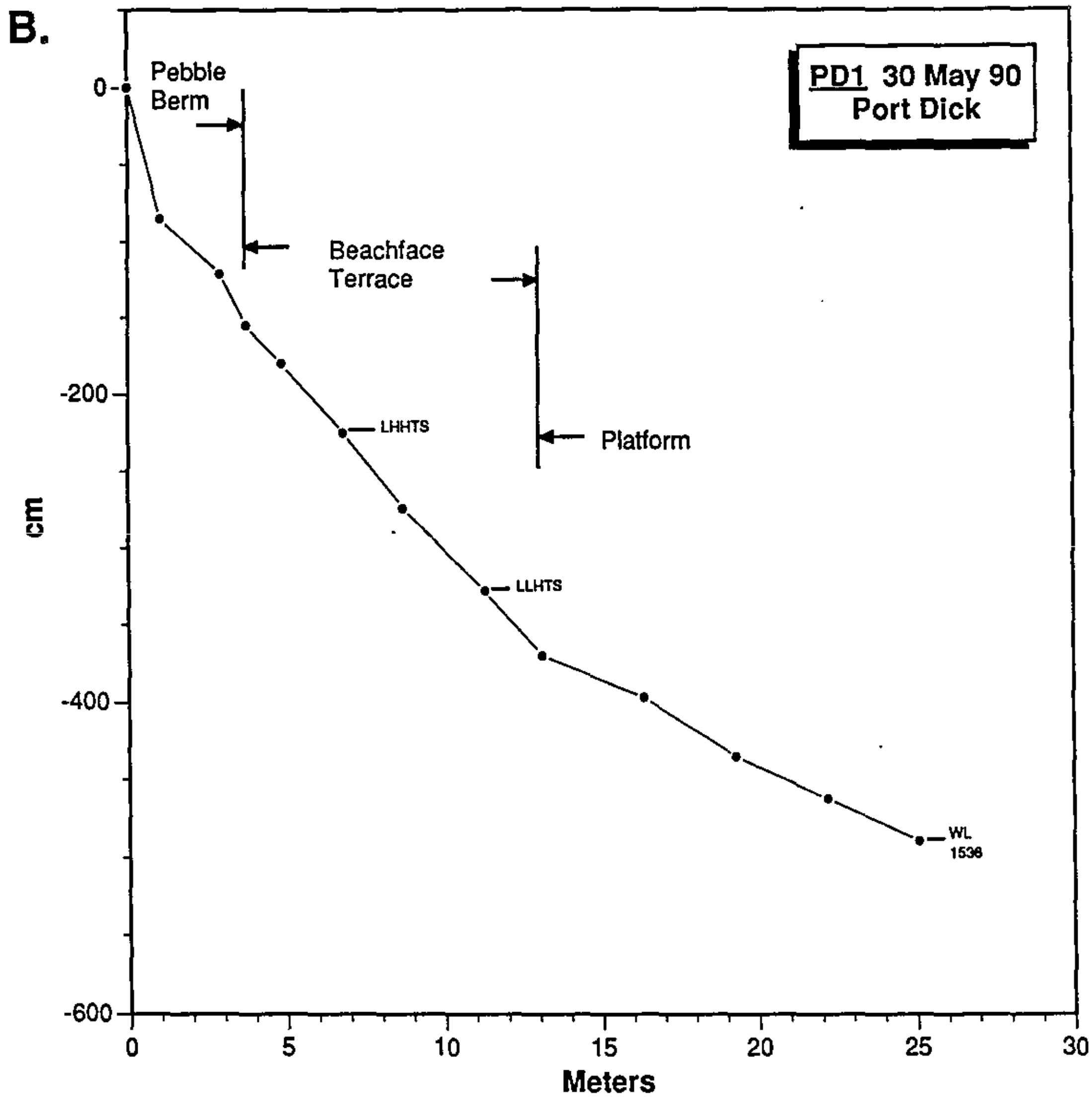


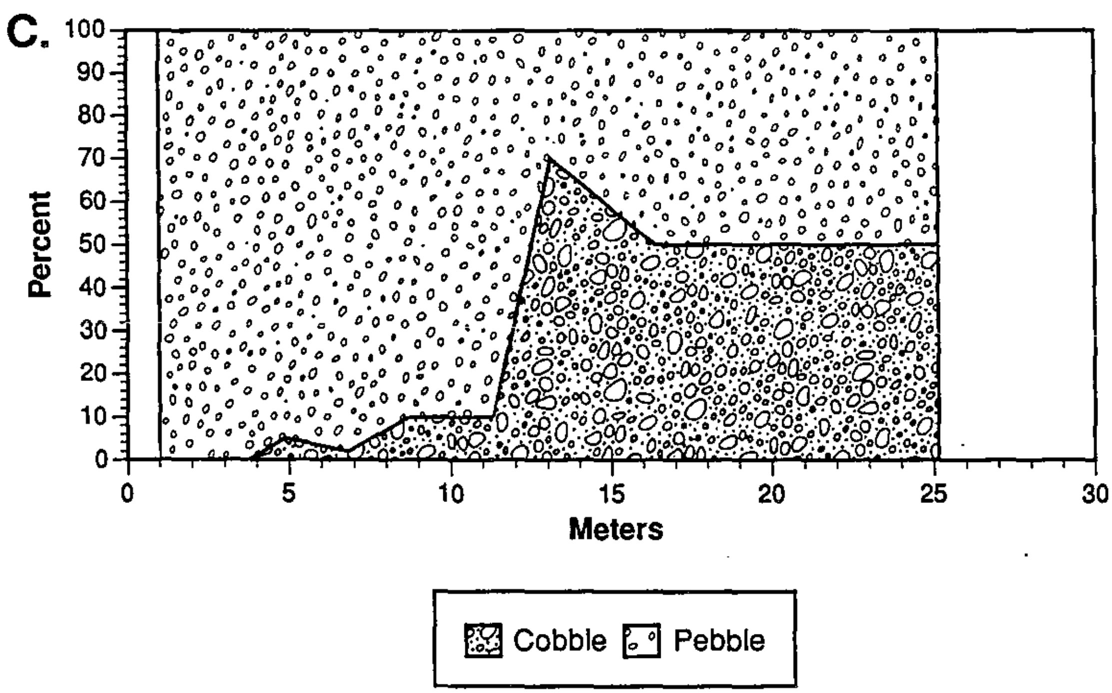
FIGURE 122. Station PD-1 on 30 May 1990.

A. Field sketch. Note beach protuberance, which is in process of covering over the asphalt pavement.

B. Topographic profile, which clearly illustrates the three morphological components of the station. Compare with sketch in A.

C. Surface sediment distribution pattern based on visual estimates at the 11 survey points (circles on diagram B). Like many of the gravel beaches in PWS, the sediments increase in size in an offshore direction.


B.
PD1 30 May 90
Port Dick
Pebble
Berm
Beachface
Terrace
Platform
LHHTS
LLHTS
WL
1536
cm
0
-200
-400
-600
0
5
10
15
20
25
30
Meters


C.
Percent
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Meters
Cobble
Pebble

IMPORTANCE OF GEOMORPHIC AND SEDIMENTOLOGIC CONTROLS

GEOMORPHIC INDICATORS

Usually, areas with abundant gravel beaches have complex geologic and topographic settings. Bedrock headlands are usually present, separating isolated coarse-grained, depositional beaches. Three geomorphic features common to such areas, crenulate bays, tombolos, and beach protuberances, uniquely affect the distribution and fate of the oil that washes ashore during a spill. We saw effects of all these features at the EXXON VALDEZ spill site.

A model of an oiled crenulate bay is given in Figure 123. These features form where dominant waves approach the shoreline obliquely, with the beach taking on a log-spiral shape on the downdrift side (away from the wave approach direction) of a protruding rocky headland. As was seen initially at the AMOCO CADIZ spill site, oil tends to come onshore and be trapped in the portion of the bay most sheltered by the bedrock headland. Oil remained on the rocks in that position on the crenulate bay discussed above at station US-5 (refer to Figs. 117 and 118), one of several on the Barren Islands, for more than a year. Crenulate bays are common features on most coastlines with gravel beaches, and, under the right wave and wind conditions, they make effective traps for spilled oil.

A tombolo is a spit-like projection of unconsolidated sediment that attaches an offshore island or rock to the mainland. They form as a result of wave refraction around the island or bedrock outcrop, which initiates sediment accumulation where the refracted waves meet in the lee of the offshore obstruction. Tombolos range in scale from a few to thousands of meters. The SSAT survey in the spring of 1990 discovered dozens of sites where oil remained on tombolos. The nature of the remaining oil included deeply buried layers in gravel, surface asphalt layers, and rock coatings, among others. An example of this type of oil accumulation, due to what we term the tombolo effect, is shown in Figure 124, a site in the Chugach Passage, Alaska. At this site, CI-1A on East Chugach Island, a 250 m long and 5-10 m wide continuous-to-broken asphalt pavement in a pebble/cobble framework remained over one year in an otherwise relatively high energy area as a result of the protection (from waves) afforded by the offshore rock platform. Another example, from Rua Cove on Knight Island in PWS, is given in Figure 125. See also the oiled tombolo described under the discussion of station N-10 (above).

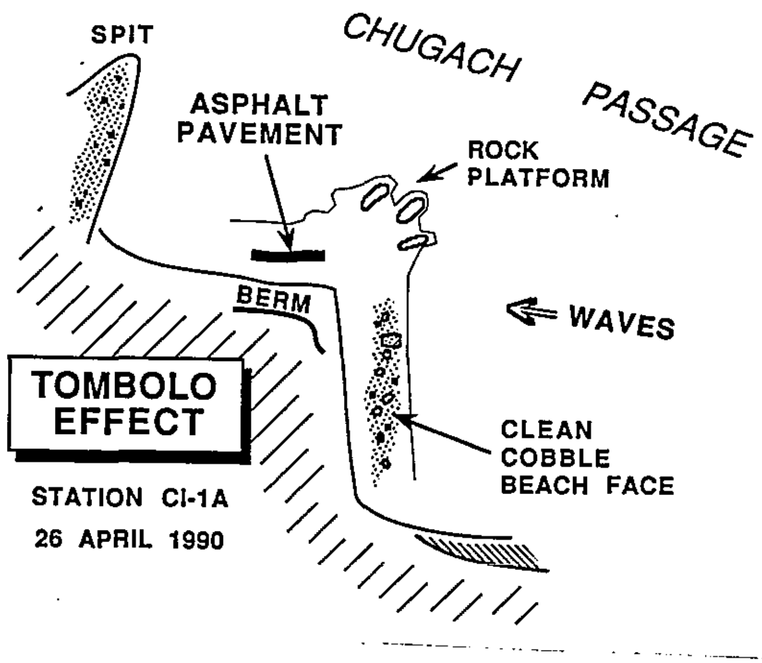


FIGURE 124. Example of the tombolo effect from the Outer Kenai area (located on Fig. 17).

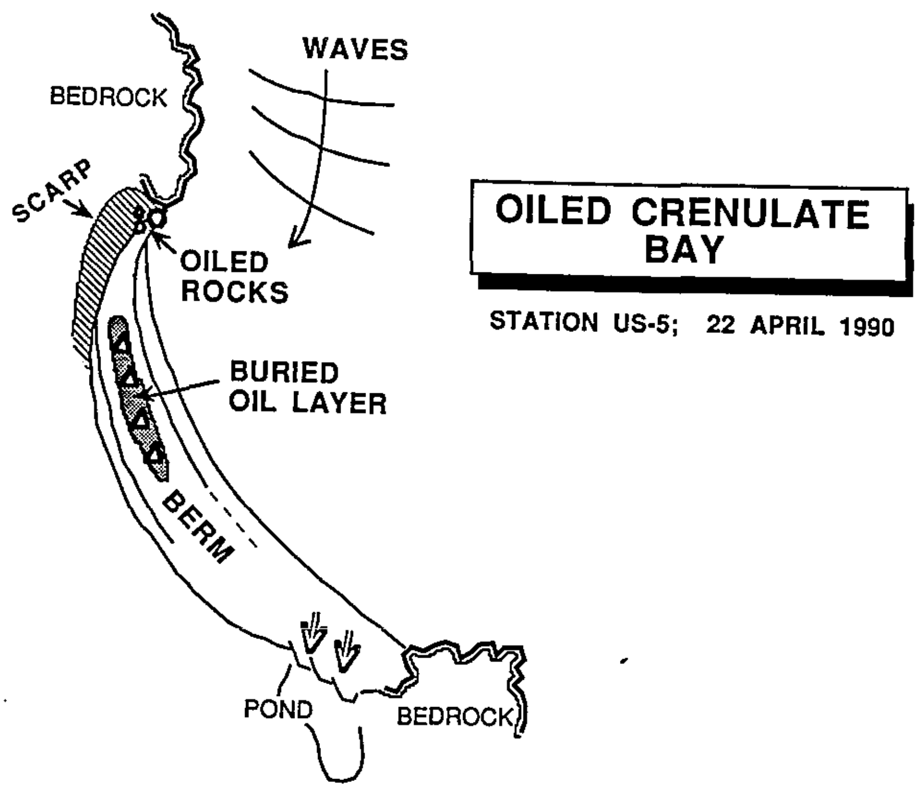


FIGURE 123. Model of an oiled crenulate bay, based on our study of station US-5 on the Barren Islands. See Figures 117 and 118 for more details.

Beach protuberances, or rhythmic topography, are common on beaches with a sustained oblique wave approach. On gravel beaches, these forms are thought to be created by dissipative waves. Under these conditions, the beach takes on a sine-wave shape (plan view), with the individual waves having a spacing of 10' to 100's of meters. They usually move alongshore en masse at annual rates on the order of their wave lengths, more or less, probably depending upon the mean longshore sediment transport rate. When oil impacts such a beach, it is most apt to be preserved in the indentions in the wavy topography. If an asphalt pavement forms, or oil penetrates into the sediments, the crest of the sediment wave has the potential to bury the oil originally deposited in the indention as it moves alongshore. The buried oil will be exposed to erosion again once a full wave length of sediment passes by. This process was observed at the METULA oil spill site, as well as at station PD-1 in Port Dick (see Fig. 122).

SEDIMENT TEXTURAL INDICATORS

The texture–the size, sorting and roundness–of clasts on a gravel beach is an excellent clue to the rate of natural cleaning of spilled oil. We observed a range of textural types on the gravel beaches in PWS, with a corresponding range in cleaning rate. The major potential textural types with respect to sorting and roundness are illustrated in Figure 126. Diagram A portrays sediment that is well-rounded and well-sorted by wave action. Typically, oil will be cleaned rapidly from a beach with this type of sediment, unless it is deeply buried. Station N-1 at Pt. Helen, which was cleaned significantly by wave action, has sediment of this type. Diagram B shows less well-sorted, rounded to subrounded particles. Beaches with this type of sediment would be cleaned naturally, but not as quickly as type A. Parts of the beach at station N-15 had sediments of this type. Diagram C shows angular to subangular, poorly sorted sediment. Gravel beach material of this type is rarely moved by the waves, therefore, if it were heavily oiled, the oil would be expected to remain for a long time. We observed this phenomena at stations N-5 and N-13 in PWS. When making these kinds of observations, one has to be aware of what Folk (1974) terms a textural inversion, which is illustrated in Diagram D (Fig. 126). The sediment illustrated in D is a mixture of moderately sorted sediment made up mostly of subangular particles. It also contains several well-rounded particles that are also well-sorted. In determining the potential for natural cleaning of such sediment, the estimated rate would have to be based on the lowest level of rounding (subangular in this case) and sorting present. The well-rounded particles were inherited from a source with a different history than this particular beach. Therefore, oil would remain on beach D for a longer time than it would at beaches A and B, but for less time than at beach C. The beach at station N-7 in PWS showed this type of textural inversion, with the more rounded particles presumably being inherited from the pre-earthquake beach. Station N-7 showed the greatest potential for long-term oil retention of all the ones in the class cobble/boulder platforms with berms.

FIGURE 125. (Facing Page) Photos of an oiled tombolo at Rua Cove, Knight Island, PWS. Both photos were taken on 25 May 1990.

A. Tombolo formed behind an exposed rock outcrop on the east shore of Knight Island, PWS (near Rua Cove). Arrow points to asphalt pavement shown in B. Photo by M. Hayes.

B. Asphalt pavement on the tombolo pictured in A. Photo by J. Michel.

A.

B.

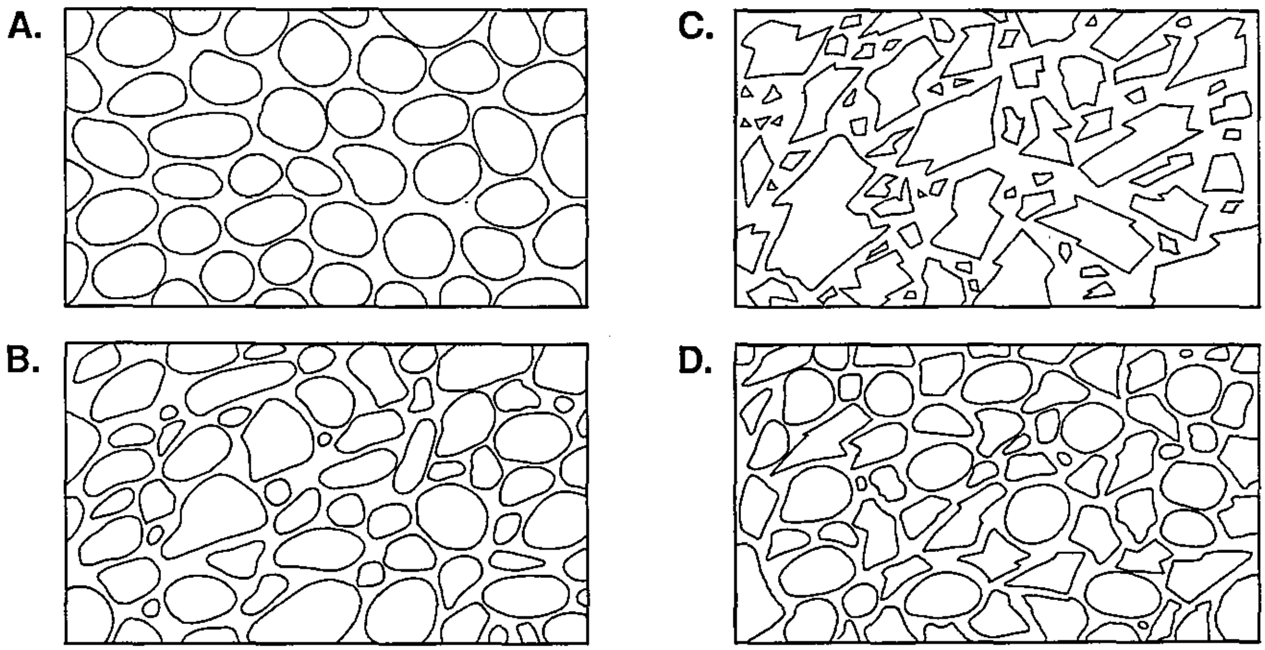


FIGURE 126. Types of textures (rounding and sorting) exhibited by the gravel beaches in PWS.

A. Well sorted and well rounded. This type of beach will be cleaned rapidly by wave action, except for the deeper subsurface oil.

B. Moderately sorted and rounded to subrounded. Natural cleaning will be somewhat slower than for type A.

C. Poorly sorted and angular. Natural cleaning will be slow.

D. Texturally inverted sediment. The well rounded clasts are inherited from a source with a different history. Estimates of rates of removal should be based on the more angular and poorly sorted particles.

POTENTIAL HYDRODYNAMIC ENERGY

Attention to the level of hydrodynamic energy expended upon a segment of coastline is a basic component of most oil-spill response programs in use today. It has been clearly demonstrated at numerous spills (e.g., Gundlach and Hayes, 1978; Hayes et al., 1980) that the exposed, higher energy environments are cleaned much more rapidly by natural processes than sheltered ones. This observation at the METULA spill site one year after the spill led to the development of the Environmental Sensitivity Index (ESI) concept (Hayes et al., 1980).

No exact quantitative measure of the potential hydrodynamic energy (PHE) of a shoreline has yet been devised. An equation for this measure should include:

Potential Hydrodynamic Energy (PHE) = wave height (average and relative frequency) + tidal energy flux (tidal range and average tidal current velocity) + water density.

We are presently working on quantifying this measure at the EXXON VALDEZ spill site. Unfortunately, direct measurements of wave heights are not available for the site, a condition that will also exist at most spill sites in the future. Therefore, indirect and hindcasting methods have to be used, such as fetch values, sediment characteristics, storm-berm volumes, and geomorphic indicators. In this document, we have referred primarily to the effective fetch. We continue to work on the development of this concept.

We know, qualitatively, that different shoreline components have widely different PHE's, because of unlike physiographic configurations, storm regimes, and tidal ranges, among other variables. This is an important consideration that should temper decision-making for specific spills. To illustrate this point, we have ranked the coastline of Alaska between the Canadian border and Kodiak Island into compartments based on energy level. We now consider PWS to have the lowest probable PHE on this coastline and the Outer Kenai Peninsula, one of the most storm-prone coastal areas in the world, to have the highest. Lower Cook Inlet and the inner passage of southeast Alaska have an intermediate ranking. As a generalization, the need for man's intervention in the cleanup process would be much greater in the lower energy areas, as is clearly shown by the EXXON VALDEZ incident, assuming the goal is to free the sheltered environments of oil within a reasonable amount of time.

SUMMARY OF OIL BEHAVIOR AND PERSISTENCE BY SHORELINE TYPE

INTRODUCTION

PWS is a complex area where each shoreline has been formed by a unique set of conditions, including the geology of the sediment source and adjacent upland, amount of uplift during the 1964 earthquake, influence of streams, and exposure to waves. This uniqueness makes it extremely difficult to make comparisons among sites. However, each shoreline type has common modes of response which affect the distribution and behavior of oil on the shoreline. In this section, we summarize the geomorphic and sedimentological controls on the initial oil behavior and short-term (1 year) persistence trends for each shoreline type.

COBBLE/BOULDER PLATFORMS WITH BERMS

A general model for the short- and long-term behavior of oil on this shoreline type is shown in Figure 127. The initial oil deposition usually covered the entire intertidal zone, because of the accumulation of large slicks against the shoreline and the relatively gentle slope (3-6°) of the platform (Fig. 127A). Very high accumulations of mousse occurred at the high-tide level as waves tended to concentrate the oil in this area. However, within a relatively short period (usually days to weeks), the oil which had stranded on the surface of the lower platform was lifted off by the tides. On most of these shorelines, the width of heavy surface oiling was 15 to 25 m. Furthermore, during spring tides and storm events, the oil was pushed up higher on the beach and over the spring berm, to the base of the active storm berm, if present. This part of the shoreline is out of the reach of normal tidal flushing, so the oil in the spring berms was very persistent, even during the storm season. In most cases, the oil was not pushed up into or on the active storm berm, because there were no very large storms during the period after the release when there were abundant heavy slicks on the water.

During the spring and summer, the heavy accumulations of mousse on the surface eventually penetrated into the sediment substrate (Fig. 127 B), the depth of penetration being limited by the volume of oil, the water table, or the presence of an impermeable layer, either bedrock or fine-grained sediments. Because of the coarse-grained nature of the sediments, the depth of penetration in the high-tide berms averaged 75-100 cm, whereas in the upper platform the average depth was about 50-60 cm. Usually, only the upper part of the lower platform had subsurface oil, to a

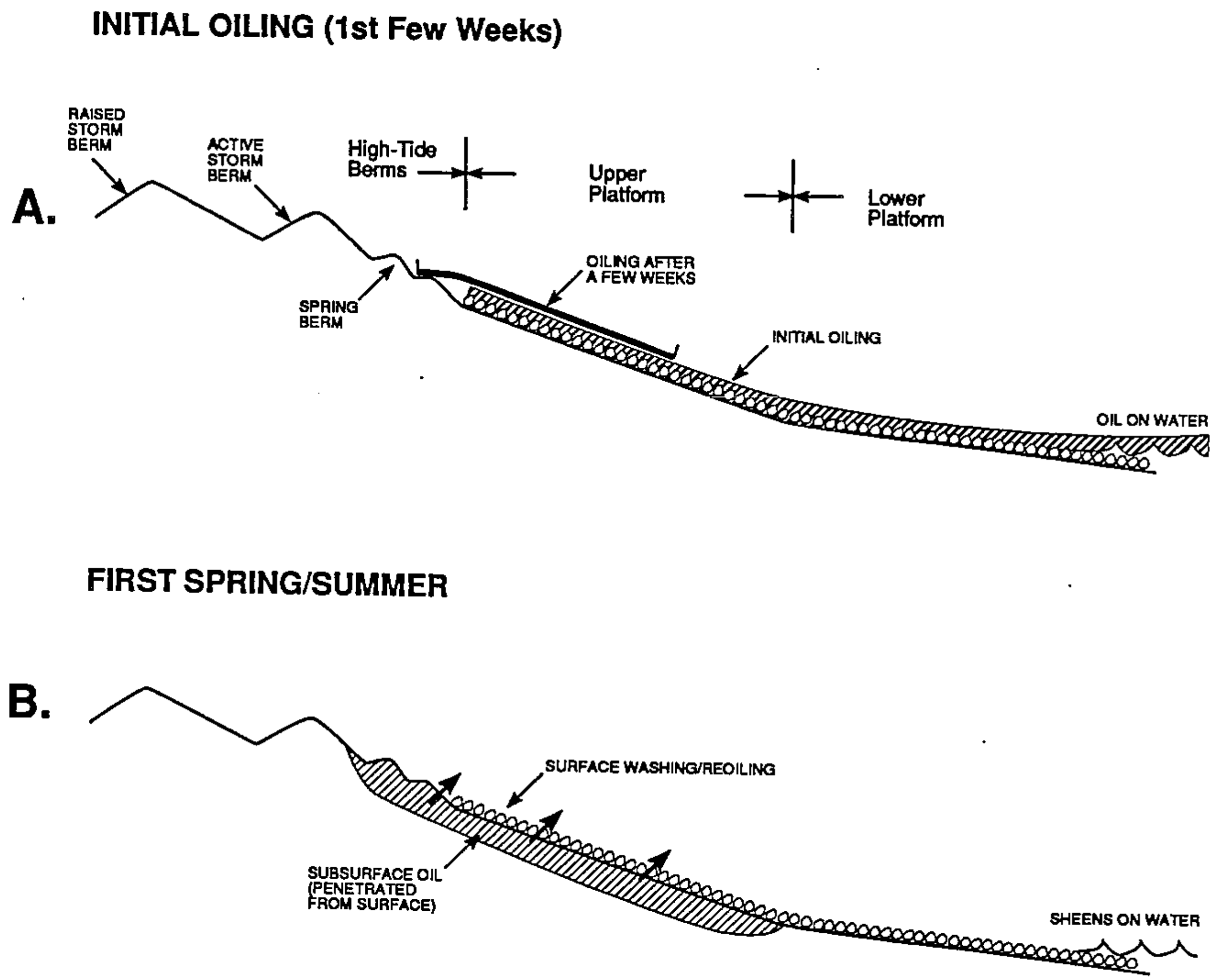
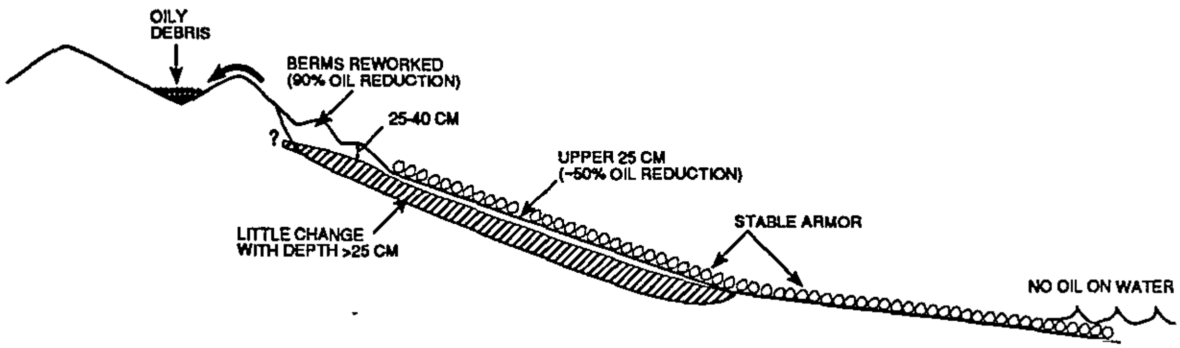


FIGURE 127. A model for the behavior of oil on cobble/boulder platforms with berms, based on our studies of the EXXON VALDEZ spill in PWS.

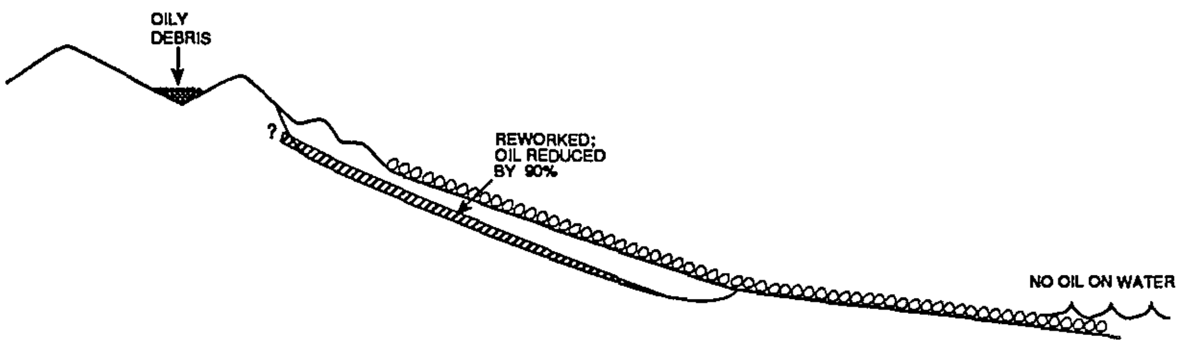
FIRST STORM SEASON (Fall/Winter)—Stable Armor (N-7)

C.



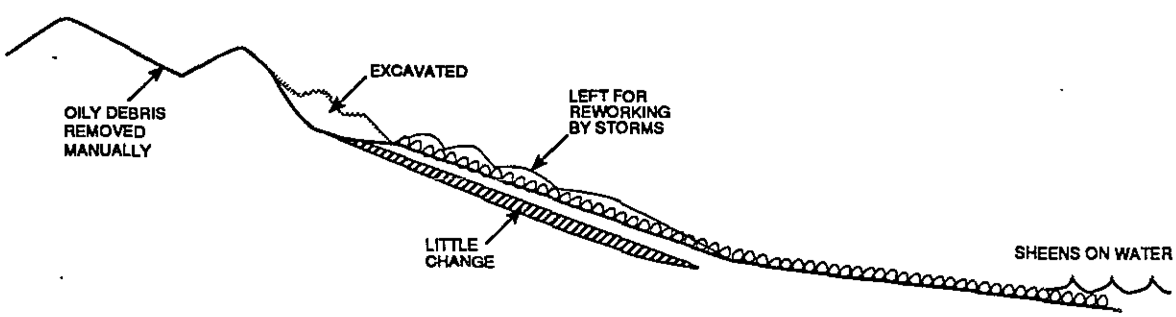
FIRST STORM SEASON (Fall/Winter)—Shallow Platform (N-4,N-17)

D.



BERM RELOCATION (2nd Summer)

E.



depth averaging about 25 cm, but the presence of subsurface oil this low in the intertidal zone is unique in our experience at oil spills. The combination of large amounts of oil, coarse-grained sediments with a stable armor, and a period of low wave energy after the spill all contributed to the deposition and persistence of oil in this zone.

The reservoir of subsurface oil was a source of mobile oil which was flushed to the surface by tidal action, generating on-going problems with the cleanup as treated beaches would quickly re-oil. These beaches with subsurface oil also were chronic "sheeners" in 1989 and 1990. The 1989 treatment regime of hot-water, high-pressure flushing had little impact on the subsurface oil. Limited field studies conducted by our team showed that little subsurface oil was removed with hot-water washing with the omniboom system. There have been frequent references to the hypothesis that the washing treatment techniques caused the oil to penetrate more deeply into the substrate, but we have not seen any evidence of this effect.

During the first storm season (October 1989 to March 1990), oil on these boulder/cobble platforms had two basic modes of behavior. Where the platform was covered with a stable armor (Fig. 127C), the only area of significant oil removal was at the high-tide berms, where erosion and deposition of the pebble/cobble berms reworked the sediments to an average depth of 50 cm. Station N-7 is representative of this mode of behavior. The stable armor effectively immobilized the substrate underlying the armor, and very high concentrations of oil remained after the first storm season ended. Armoring of the platform is a major factor in the fate of oil on this shoreline type. Sediment from the upper and lower components of the shoreline is transported across this platform but the armor remains intact. The only conditions under which the armor will be mobilized is during extreme storm events, such as a ten-year storm. The inherited bedrock platform, which produces a gentler than average beach slope, also contributes to the formation of armor.

On shorelines with a very shallow bedrock platform, such as at Pt. Helen and N-4 on Smith Island, storms mobilized a large percent of the sediments on the platform and the oil was removed to the depth of the active sediment envelope (Fig. 127D). This process was a major mechanism for oil removal with depth. The most exposed sites showed the greatest change, with a maximum depth of reworking of 50-75 cm. There was no landward migration of the true storm berm; it was not activated during this period. The erosion/deposition of the high-tide berms was up and down the beach or alongshore. There was still subsurface oil present during the summer of 1990, but the concentrations were very much lower.

As of summer 1990, on all cobble/boulder platforms with berms, the surface sediments were mostly clean with only thin stain remaining on some clasts. Frequently, there was a band of heavily oiled debris at the base of or behind the storm berm. Oil still remained in the spring berm, below a veneer of clean sediment. At a number of these sites, the spring berm was relocated to the upper intertidal zone (Fig. 127E). In some localities where the subsurface oil remained in the upper platform, the excavated sediments were piled on top of it. These relocated sediments were left to be reworked and transported back up the beach by storm waves.

In 1991, after a second storm season, we do not expect significant changes in the overall pattern of oil persistence. Depending on the severity of the storms, the subsurface oil will be further removed, but only to the depth of sediment mobilization. On exposed beaches with a shallow bedrock platform, a second season of high wave conditions will continue to remove the oil. The only exception would be for oil high up in the spring berm. On those shorelines with a stable armor, the subsurface oil will persist at high concentrations, until the armor is mobilized. These shorelines will pose the greatest problem for treatment in 1991 because of the relatively large amount of oil present, the degree of disturbance of the surface that would be needed to remove the armor, and, particularly, the fact that the oil extends to below the middle intertidal zone, where biological impacts from physical disruption would be great. During the 1991 spring shoreline surveys, special care should be taken to identify sections of shoreline where a stable armor may be shielding subsurface oil from natural removal.

There was only one set-aside for this shoreline type, a small pocket beach in the south end of LA-15E, which was studied by Exxon. Station N-15 on the northeastern end of Latouche Island, which was heavily oiled, was quickly washed with hot water and then treated with Inipol in 1989, so it may be the most representative of how a set-aside site might behave. All the other stations in this class were on sites which were repeatedly treated with hot-water washing. Based on our studies, there were no significant differences in the removal rates of surface or subsurface oil among those sites heavily treated versus those lightly treated. These types of shorelines are among the most exposed in PWS and the surface sediments were equally cleaned over the storm season. N-15 had 75-85 percent of the surface oil removed by May 1990; stations N-3 on Smith Island and N-7 on Knight Island had 85-90 percent removed. Pt. Helen (N-1) and N-4 on Smith both showed 95 percent surface oil removal, because of the higher degree of sediment reworking on these beaches with shallow platforms. The only benefit of hot-water washing was the recovery of some amount of oil, rather than allowing it to be released into the water column during storms. This benefit has to be weighed against biological impacts to the intertidal communities resulting from the treatment itself.

The oil behavior on PWS gravel beaches was very different from oil on gravel beaches along the Outer Kenai Peninsula and Kodiak/Shelikof region. In PWS, the subsurface oil occurred as a result of oil penetration into permeable surface sediments. We saw few examples of oil being buried by the transport of clean sediments onto oil deposits. Some notable exceptions were on pebble beaches and tidal flats with swash bars. In contrast, outside PWS burial of oiled sediments was much more common and posed a special set of cleanup problems. An extreme example is the buried oil layers on the Barren Island beaches (US-5, 10).

RAISED ROCKY PLATFORMS WITH MINIMAL SEDIMENT

The initial stranding of oil on this shoreline type at station N-2 occurred mostly at the high-tide line. Wave refraction kept the oil offshore and/or the algal growth on the bedrock in the middle and lower zones prevented the oil from adhering to the bedrock surface. Because of the lack of a significant amount of sediment, there was limited subsurface oil or persistence of oiled sediments on this type of shoreline. We saw ample evidence that where the surficial oil was a thin coat, weathering processes were steadily removing it. However, the irregular bedrock surface has small, sheltered microenvironments, mostly in crevices or depressions in the bedrock surface, where the oil was very persistent. These crevices oftentimes contained thick accumulations of oil consisting of relatively fresh oil below the surface crust. There was little change in the distribution of these thick oil deposits over the period September 1989 to September 1990. About one-third of the surface oil was removed during this period, primarily from the splatter zones. The thick oil accumulations generated sheens on the surface of tide pools, even as late as September 1990. The oil eventually will weather into tar, with little potential for remobilization. No further cleanup efforts are recommended for this shoreline type, other than manual removal of oiled debris that accumulated over the storm season.

BAYHEAD BEACHES

Many bayhead beaches were heavily oiled, being a major accumulation zone for oil slicks blown into the bay. The deepest penetration of oil in PWS was observed in beaches of this type (i.e., at Sleepy Bay). The intertidal sediments on bayhead beaches are relatively permeable and thick because they are depositional in nature and reworked only occasionally by waves and stream migration. Therefore, they have the potential for long-term retention of subsurface oil. The sediments are finer-grained than the cobble/boulder platforms, but do not have armoring. Because they are finer-grained, it takes smaller waves to mobilize the sediments, although any boulders present will mostly remain in place.

The wave climate in this setting is low and intermittent enough that once oil is deposited in the sediments, it tends to remain at depths below the active sediment envelope. The finer-grained sediments (pebbles) readily form, erode, and reform small high-tide berms, especially with a neap-to-spring buildup of the berm. This process comprises the sediment envelope on the upper beach, which can be as much as 50-70 cm. However, oil penetration can reach below this depth. Thus excavation of the spring berm down to clean sediments was probably the only way to assure the removal of oil from this zone within a reasonable time period. The mobility of the sediments would quickly reconstruct the beach profile.

In most cases, the stable central ramp does not have a stable armor, although there are coarser sediments on the surface. We did see erosion of this section, for example, when the entire profile was lowered at Sleepy Bay where erosion may have been triggered by migration of the stream channel. Sediments migrate across the ramp, but the subsurface sediments are not mobilized, thus any subsurface oil is likely to persist unless mechanically disturbed. The permeability of these finer-grained beaches is much lower than the cobble/boulder platforms, so flushing rates would be slow, as well.

Migration of swash bars on the tidal flats poses the potential for burial of oil under clean sediment. This process can be very slow where wave activity is infrequent (e.g., N-14 in Northwest Bay), but, consequently, the oil could be buried for a long period before being re-exposed.

From a strict oil persistence perspective, bayhead beaches benefitted greatly from treatment activities. With the heavy degree of oiling, coarse sediments, and sporadic wave energy of this shoreline type, there would have been little natural removal, particularly with depth. As it was, treatment activities removed much of the oil, leaving behind oil mostly in the form of thin films which were readily removed. However, asphalt pavements had already started to form in 1990 at sites where the oil had not been completely removed in 1989. These shorelines have great potential for long-term persistence of oil under the following conditions:

1. Subsurface oil in the spring berm, where the oil was pushed above the zone of normal tidal action.
2. Subsurface oil in the mid-beachface or stable central ramp which is below the level of routine sediment reworking.
3. Surface oil in areas protected from daily weathering processes, such as in the wave shadows behind large rocks and the sides and undersides of surface cobbles and boulders.

This shoreline type will continue to pose problems for cleanup in 1991. Berm relocation was only partially effective in that it targeted removal of oil only from the spring berms. Natural removal of the subsurface oil in the middle part of the beach will be very slow. Yet, as was stated for cobble/boulder platforms, this residual oil is located in the area where any mechanical removal will surely have significant impacts to the intertidal community. Therefore, the issue will be whether there is a net benefit in the removal of this residual oil over allowing it to weather in place.

PEBBLE BEACHES WITH TIDAL FLATS

On these types of shorelines, where the beachface had depositional berms, such as at N-8 on Block Island near the refueling depot, the oil penetrated to about 25 cm. Otherwise, the depth of penetration was limited commonly by peat layers. The peat also forces discharge of ground water at a higher than usual elevation of the beach, which speeds natural removal and degradation of the oil. The presence of pebbles indicates that low-to-moderate wave energy impacts this type of shoreline on a seasonal basis. It may be several years before sufficient wave activity reworks the sediments to the depth of oil penetration. However, treatment activities were fairly successful in removal of oil from the top 20 cm or so, because of the fine-grained nature of the substrate.

The biggest concern on this shoreline type is the potential for impacts to the tidal flats. In all cases, the tidal flats showed some contamination at the surface and shallow subsurface, probably related to cleanup activities and the transport of contaminated sediments onto the flat during high-pressure water washing. The only station which could be considered a set-aside for this shoreline type was the tidal flat off of N-11 and N-12 on Crafton Island, where only manual removal and bioremediation were conducted. At this station, we saw much less contamination of the tidal flat, on the surface and with depth, than at the very wide flat on Block Island (N-9). The paucity of tidal flats in PWS spared this shoreline type from serious impact.

ROCKY RUBBLE SLOPES WITH RAISED BAY BOTTOMS

Two of our stations on this shoreline type were on set-asides which were heavily oiled, so there is information for comparison of oil distribution and persistence for hot-water washing versus no treatment. For the heavily oiled set-asides, oil persisted as a dry coating on the rocks. Although there was an average of 80 percent removal of this surface coating over the period between September 1989 and September 1990, the remaining oil coat was much thicker than the oil on treated areas and represented a much larger amount of oil on the shoreline. We also observed the formation of pavements as the oil accumulated on the surface at the base of the rubble veneer. These thick oil deposits can persist for very long periods because they are in an even more sheltered microenvironment. Washing under these conditions would remove a significant amount of oil which would otherwise persist for long periods. We are not sure if washing resulted in higher contamination of the lower intertidal zone, because of the high variability of the chemical results.

A second problem is the penetration of oil into subsurface sediments. The coarse, poorly sorted rubble can be permeable because of the lack of sorting and reworking by wave activity, and the lack of a soil horizon. If it is rubble on bedrock, as it is at station N-5 in Snug Harbor, there is little potential for penetration. However, if the rubble layer is thick, then there is the potential for oil to penetrate deeply, for example, up to 45 cm at N-13, a set-aside in Herring Bay. The oil probably did not penetrate into the crevices between the surface rubble immediately. Thus, if it had been possible to quickly remove the heavy surface oil accumulations, this subsurface oil contamination might have been prevented. Of course, the extent of shoreline contamination in PWS was so large and the cleanup so logistics-intensive, it was difficult to prioritize cleanup activities. At smaller spills, removal of oil from these sheltered, rubble shorelines should receive high priority because of the potential for long-term persistence. Although there is great potential for impacts to the intertidal communities, from a strict oil-persistence perspective, this shoreline type benefits from treatment efforts when in a very sheltered setting.

ROCKY SHORES

The three rocky shorelines studied in this project probably only scratched the surface of the possible ways that oil could affect rocky coasts. Furthermore, each of the three stations was exposed to a different degree of wave energy. The order, in decreasing energy, was N-16, N-10, N-6. The one overriding theme is that exposed-to-moderate rocky coasts create tombolos where the longest-term residence of oil is going to take place. Tombolos tend to be zones of accumulation of oil, both during the spill and as oil is removed from adjacent shorelines. For example, at station N-10 in Herring Bay, only about 25 percent of the surface oil at this site was removed from September 1989 to May 1990, even though it is relatively exposed to waves. Most of the oil was being preserved in a pebble tombolo behind the rock headland. Tombolos are commonly composed of thick, permeable sediments where oil can penetrate and persist.

On highly sheltered rocky coasts (N-6; Bay of Isles), the oil persisted in the crevices, on the vertical rock faces, and on the undersides of the sediment veneer. The oil was removed from the horizontal rock faces more quickly, probably by dessication, photo-oxidation, and physical flaking. Even on the most sheltered shorelines, natural weathering processes have resulted in the removal of at least 50 percent of the surface oil from this shoreline type.

As stated above for rubble slopes, these shorelines benefitted from cleanup efforts, considering only the persistence of oil in the upper intertidal zone. Since the lower tidal zones were composed of bedrock, there was little potential for transport of oiled sediments from the upper to the lower zones as a result of treatment. However, there is significant potential for impacts to the rich biological communities in the lower zones directly related to cleanup efforts. There are few cases where this shoreline type requires further treatment in 1991, beyond manual removal of oiled debris that may have accumulated over the storm season.

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APPENDIX A

Preliminary Results of Shoreline Monitoring Survey of the Exxon Valdez Spill in Prince William Sound, AK

PRELIMINARY RESULTS OF SHORELINE MONITORING SURVEY OF THE EXXON VALDEZ SPILL IN PRINCE WILLIAM SOUND, AK 19-25 JANUARY 1991

Jacqueline Michel[1] and Miles O. Hayes[1]

EXECUTIVE SUMMARY

Field surveys were carried out for seven days in late January 1991 using the USCGC Sweetbrier as a base for logistical support. The support provided by the Sweetbrier was excellent. We missed no scheduled field time and completed all the surveys as planned. Two field teams revisited 15 of NOAA's permanent study sites, as well as 9 berm relocation sites. Weather conditions ranged from heavy snow and rain to clear with temperatures usually in the mid-thirties. All of the beaches were backed by deep snow drifts and many were frozen in the upper intertidal zone. Between 3 and 5 trenches were dug at each site, usually to the depth of the water table, and 35 oiled sediment samples were collected for chemical analysis. Videotapes were recorded for most of the sites.

With respect to the permanent NOAA stations, no major surprises were discovered, because, for the most part, they continue to show trends described in our report on the summer 1990 research. The stations we term cobble/boulder platforms with berms show a range of conditions, but generally, they retain subsurface oil in the mid- to upper-intertidal zone where it is secured by a surface armor of cobbles and boulders. The permanent stations that had berm relocations, N-3 and N-4 on Smith Island, N-17 on Perry Island, and N-15 on Latouche Island, were relatively clean in the berm zone, but those stations with subsurface oil in the middle parts of the profile generally retained it. Stations with shallow, steep bedrock platforms, such as N-1 at Pt. Helen, N-4 and N-17, continued to show evidence of cleaning by hydraulic flushing. On the other hand, stations with deeper sediment veneers and flatter slopes, such as stations N-7 on Knight Island

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1 Research Planning, Inc.
Post Office Box 328
1200 Park Street
Columbia, S.C. 29202

and N-3, retained considerably higher quantities of subsurface oil than that found at the other stations.

The two permanent sites we classify as bayhead beaches, N-14 in Northwest Bay and N-18 in Sleepy Bay, were significantly dissimilar with respect to the nature of the remaining oil. Station N-14 has only a few scattered patties in the lower intertidal zone, but large quantities of buried oil remain at the station in Sleepy Bay (N-18), where erosion of surface sediments has exposed patches of formerly buried oil along the upper one third of the profile.

All of the sites we visited that had been subject to berm relocation in the summer of 1990 had been returned to normal–appearing topographic beach profiles by wave action. In many instances, the sediment on the beach had not been resorted to its original textural configuration. Surface armoring had not been restored at any of the locations where berm relocation had disrupted it.

Except for a site at the south end of Pt. Helen (KN-405A), surface oil was scarce on these beaches. However, most of the berm relocation sites we visited that were composed of medium to fine gravel (small cobbles and pebbles) had subsurface oil in the middle and lower intertidal zones, usually at depths of 40-60 cm. The subsurface oil ranged from stain to "heavy OR", that is, heavily oiled but not to the point that the pore spaces were saturated, and when exposed to salt water, it sheened readily.

The stations visited that are classified as pebble beaches with tidal flats, stations N-11 on Crafton Island and N-9 on Block Island, retained traces of shallow subsurface oil which produced minor sheening, but otherwise, were continuing to improve. The stations classified as rocky rubble shores that we revisited, stations N-13 in Herring Bay and N-12 on Crafton Island, continue to show steady removal of the surface oil.

It is clear from our observations that the major remaining question regarding treatment of the EXXON VALDEZ spill site is how to deal with the subsurface oil. Where oil remains in high-level berms, berm relocation similar to that carried out last year appears to be effective in removing the oil with minimal impact to the environment. Oil buried under armor on the platforms of some beaches presents a more difficult problem. Overturning the armor and exposure ("tilling") of the oiled subsurface sediments is a mechanism that would surely allow most of the oil to be removed by wave action. A decision to do this will have to be weighed against the impact of "tilling" on the biota of that zone. There may be also some loss of fine sediment from the beach before the armor is re-established.

Our observations do not provide conclusive evidence on the effectiveness of the bioremediation efforts of the past two years. We see no evidence of any effect on subsurface oil. We did have a sense of some enhancement of surface oil removal at certain sites, such as at stations N-11 on Crafton Island and N-18 in Sleepy Bay. However, our studies were not designed to measure the effectiveness of this technique.

INTRODUCTION

A continuation of NOAA's monitoring program of the beaches of Prince William Sound (PWS), Alaska that were oiled during the EXXON VALDEZ spill was initiated on 19 January 1991 and continued for seven days without interruption. Despite highly variable weather conditions, which included heavy snow and rain and high winds, the objectives for each day were met, primarily as a result of the excellent logistical support provided by the U.S. Coast Guard Buoy Tender Sweetbrier. Two field teams visited a total of 24 sites, which are outlined in Table 1 and located in Figure 1. Despite the fact that heavy snow drifts were present behind all the beaches and some of the upper intertidal zones were frozen, it was still possible to find most of the permanent survey markers and carry out the surveying and sampling as planned.

TABLE 1. List of stations visited on 19-25 January 1991 using the USCGC Sweetbrier.

Sites Visited	Location Name	Profile[1]
N-1	Pt. Helen	N-1
KN-405A	Pt. Helen	x
N-3	Smith Island (Berm Relocation)	N-3
N-4	Smith Island (Berm Relocation)	N-4
N-7	Knight Island	N-7
N-9	Block Island	N-9
EL-011A	Block Island (Berm Relocation)	x
N-10	Herring Bay	N-10
KN-113A	Herring Bay (Berm Relocation)	x
N-11	Crafton Island	N-11
N-12	Crafton Island	N-12
N-13	Herring Bay Set-Aside	N-13
N-14	Northwest Bay	N-14
EL-056C	NW Bay (Berm Relocation)	E-B3
EL-057A	NW Bay (Berm Relocation)	A-
N-15	NE Latouche Island	N-15
	NE Latouche Island	N-15X (E-4B)
	NE Latouche Island	N-15Y (E-11)
N-17	Perry Island (Berm Relocation)	N-17
N-18	Sleepy Bay	N-18
LA-20C	Sleepy Bay (Berm Relocation)	
KN-209D	Knight Island (Berm Relocation)	A-
KN-209A	Knight Island (Berm Relocation)	x
SP-019A	Sphinx Island (Berm Relocation)	

[1] Indicates designation of which profile was measured. N=NOAA profile; E=Exxon profiles; A=ADEC profiles; x=new profile.

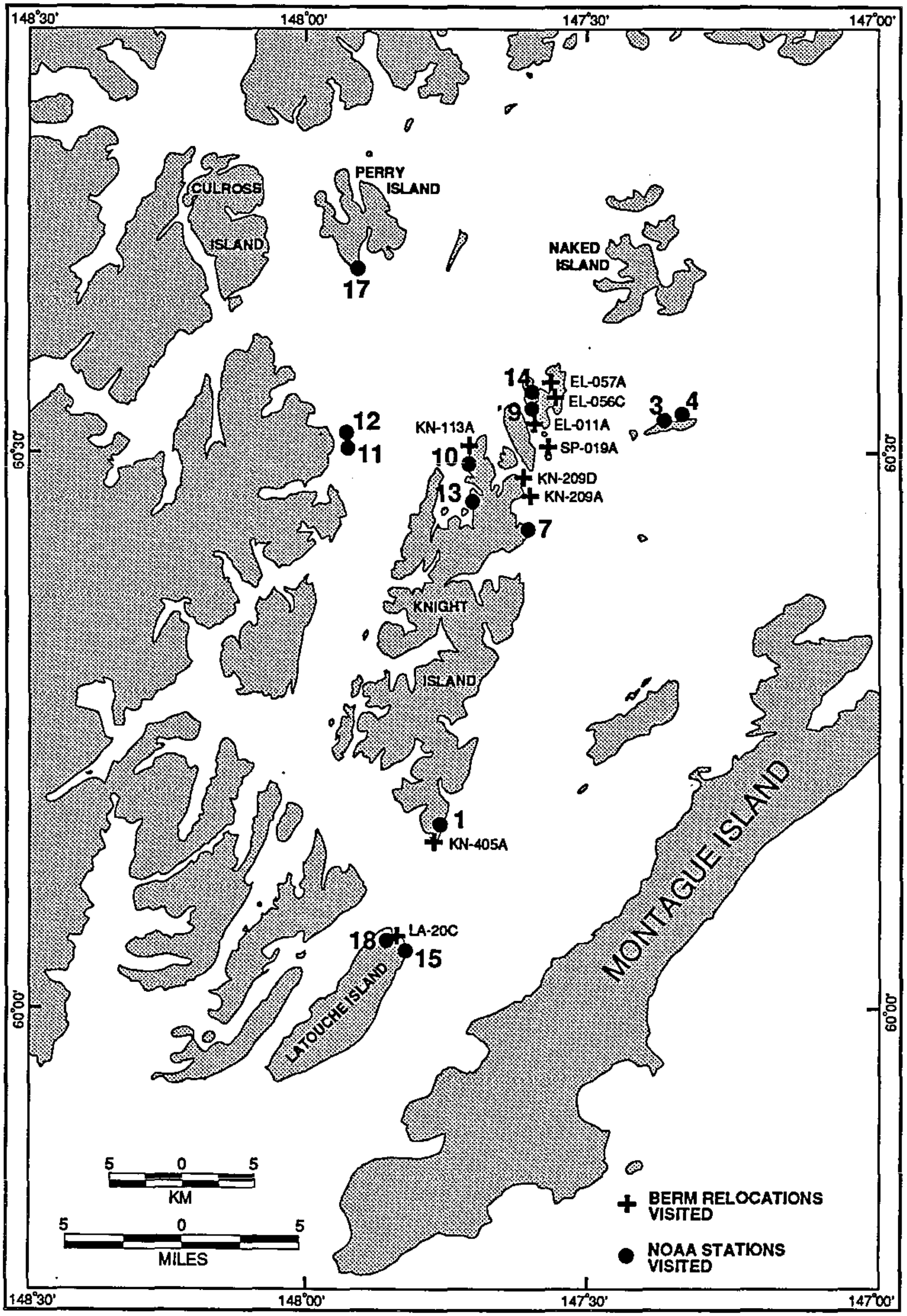


FIGURE 1. Location of the field study sites visited by NOAA's field teams during the 19-25 January 1991 field survey.

ACKNOWLEDGEMENTS

This report on the January field survey of the EXXON VALDEZ spill site describes an important component of the continuing monitoring survey sponsored by the Hazardous Materials Research Branch of NOAA, John Robinson, Branch Chief, and David Kennedy, Project Technical Coordinator. The U.S. Coast Guard provided an excellent base of operations, the USCGC Sweetbrier. Commanding Officer William D. Wiedenhoeft and Executive Officer Maurice K. Jenkins, as well as all the other members of the crew, were most cooperative in making the survey a complete success. Exxon provided financial support for part of the endeavor, including air transportation from Cordova to Anchorage.

The field surveys were conducted by two field parties. One of the teams, led by Jacqueline Michel of RPI, included David Serena of RPI and Joe Golas of NOAA, and the other team, led by Miles Hayes of RPI, included Stephen Lehmann and Debra Simecek-Beatty of NOAA. Lieutenant JG Ivan Nance went in the field with either of the teams each day and shot videotapes of most of the sites he visited.

DATA COLLECTED

A total of 24 sites were visited during this survey (Table 1; Fig. 1). With the exception of berm relocation sites LA-20C and SP-019A, which were inspected visually and photographed, the following data were collected at each station:

1. Topographic profiles were measured. The profile designation shown in Table 1 indicates which profile was run; N for NOAA profiles; E for Exxon profiles; and A for ADEC profiles. An "x" indicates that a new profile was established to show the general beach morphology, without being tied to any previous survey.
2. Along the profile, estimates were made of surface oil coverage and sediment distribution.
3. Detailed trench descriptions were recorded.
4. Samples were collected at selected depths. A total of 35 samples were collected and sent to LSU for analysis of TPH concentrations. Selected samples were characterized by GC/MS analysis. The TPH results are shown in Table 2.
5. The site was recorded on videotape.

Our field team also visited the three sites where Exxon's time-lapse photography studies are in progress. The windows for the cameras were cleaned. They all appeared to be in working order.

SUMMARY OF OBSERVATIONS

INTRODUCTION

The following is a brief discussion of the more critical observations made during the January 1991 survey. In addition to revisiting NOAA's permanent field stations, a total of 8 additional berm relocation sites were visited. The berm relocation sites were classified according to the morphological categories worked out last summer for NOAA's permanent stations and they are discussed below under the appropriate heading.

COBBLE/BOULDER PLATFORMS WITH BERMS

Introduction

A total of eleven of the sites visited fall in this category. This shoreline type constitutes a disproportionate percentage of our stations relative to its occurrence in

TABLE 2. Sediment TPH (in ppm) for samples collected during the January 1991 survey.

Cobble/Boulder Platformwith Berms

Station No.	High-Tide Berms < 25 cm	High-Tide Berms > 25 cm	Upper Platform < 25 cm	Upper Platform > 25 cm	Lower Platform
N-1		2,280		590	
N-3		350		4,210/17,400	1,350
N-4		230			
N-7		2,460		10,400/18,000	
N-15			10,500		
N-17		1,540			

Bayhead Beaches

	High-Tide Berms		Central Ramp		Low-Tide Bars
N-18		17,600	<50	34,900	<50
EL-057A			7,720		
EL-056C				2,120	

Pebble Beaches with Tidal Flats

	Upper Beachface		Lower Beachface		Tidal Flat
N-9				<50	450
N-10Y		3,600			
N-11	9,920		140		
EL-011A			8,500/21,900		

Rocky Rubble Shores

	Rubble Slope
N-13	500/1,500
N-12	<50/<50

PWS, primarily because of the propensity for these beaches to retain subsurface oil. Cobble/boulder platforms with berms consist of three components: (a) high-tide berms, the landward portion of the beach which is usually composed of storm or high-tide deposits of gravel with beachfaces that slope seaward on the order of 10-15°. The potential for oil penetration is great in this area, because of the thickness of the porous gravel; (b) upper platform, a relatively flat (3-6°) eroded rock bench originally carved by wave action and now covered by a relatively thin veneer of coarse sediment, which is usually armored at the surface; and (c) lower platform, a surface analogous to the upper platform except that it usually slopes seaward at a smaller angle and is typically covered by coarser sediments, usually boulders.

Pt. Helen, Knight Island

Two stations were visited at Pt. Helen, NOAA's permanent station N-1, which is located approximately 100 m north of a large, conspicuous rock outcrop in the intertidal zone, and KN-405A, which is located approximately 200 m south of the rock outcrop. Although the surface of profile N-1 appeared to be highly reworked, with abundant bars and ridges, comparison of the surveyed profile with earlier surveys revealed no major topographic changes. On the surface of the upper half of the beach there was 5-10 percent occurrence of mousse-covered cobbles which had been reworked from the subsurface, indicating some turnover of the beach sediments. Subsurface oil, which occurred in two of the three trenches dug, appeared to be lighter, consisting mostly of stain on cobbles and boulders, than was observed during earlier surveys of this site. A sample collected at a depth of 36 cm at the base of the high-tide berm contained 2,280 mg/kg TPH, which is within the range of previous samples. Oil in the upper platform is highly variable. In January 1991, one sample from 40 cm had 590 mg/kg, about an order of magnitude lower than a sample collected in January and September 1990, but about the same as samples collected in November 1989 and February 1990. The rock platform is relatively steep (6°) and the sediment veneer is thin, as evidenced by the abundant rock outcrops along the raised platform. These two factors are thought to promote hydraulic flushing of the subsurface oil at this station (Hayes, Owens and Pavia, 1990).

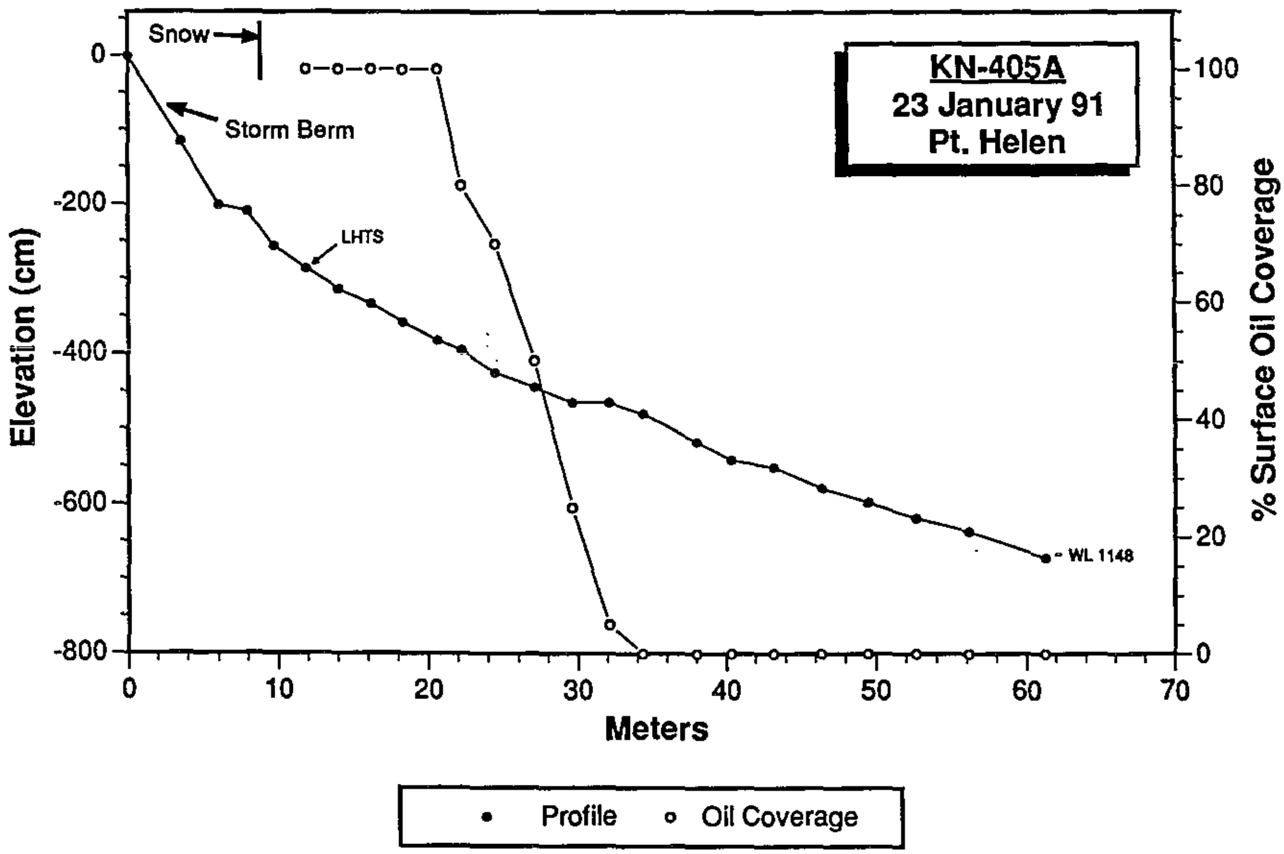


FIGURE 2. Plot of beach topography and surface oil coverage at a new station established at KN-405A on 23 January 1991. This was the most heavily oiled area we visited on this trip.

A plot of the beach profile measured at KN-405A, as well as surface oil distribution, is given in Figure 2. The profile starts with a two-meter-high storm berm, with the rest of the intertidal zone being a fairly typical, moderately sloping rock platform covered by a gravel veneer. Very heavy surface oil extended for 15 m from the high-tide line (Fig. 2), indicating no significant reworking to date. Heavy subsurface oil occurred throughout this zone, to depths greater than 42 cm. The reason for this occurrence of heavy oil, especially in comparison with the relatively light oil at station N-1, is something of a mystery. Exxon is shooting time-lapse photography of this site over the nonsummer months in order to understand why this particular section of Pt. Helen has not shown any evidence of reworking of the surface sediments. We did not visit the berm relocation site on the southern tip of Pt. Helen.

Smith Island

NOAA has two permanent station on the north side of Smith Island, N-3, which is located about one third of the way from the western end of the island, and N-4, which is located about one third of the way from the east end. Both stations were subject to berm relocation in the summer of 1990.

The topographic changes of the beach profile at station N-3 relative to the berm relocation project are shown in Figure 3. Plot 3A illustrates the excavation of the top of the berm that was carried out in August 1990. The relocated material had not been modified by waves to any significant degree by the time of the 7 September 1990 survey. As shown by plot 3B, however, the profile had returned to near its original configuration by 21 January 1991. Note the total recovery of the active storm berm to the May 1990 configuration in January 1991 that is shown in plot 3C.

Despite the evidence given in Figure 3 of the large amount of reworking sediments underwent at this site, the beach retained considerable oil, except in the berm area where subsurface oil was very light down to 42 cm. TPH levels in the berm substrate dropped from 3,500-7,500 mg/kg in 1990 samples to 350 mg/kg in the January 1991 samples (trench A). A heavy surface oil film occurred on the upper platform, and it remained medium-to-heavily oiled from the surface to 42+ cm, over the same area as observed during previous surveys. As shown in Table 2, two samples from the upper platform (trenches B and C) contained 4,210 and 17,400 mg/kg oil, showing no change from previous data. A sample from 20-25 cm depth on the lower platform (trench D) contained 1,350 mg/kg oil, the highest level observed in this area since January 1990. The four trenches dug along the profile are illustrated in Figure 4. Note the preservation of subsurface oil under a protective armor in the trenches lower on the profile. Berm relocation appeared to be very effective in reducing oil con-centrations in the spring and high-tide berms. However, there may have been some slowing of oil removal from the intertidal zone which was covered by the relocated sediments.

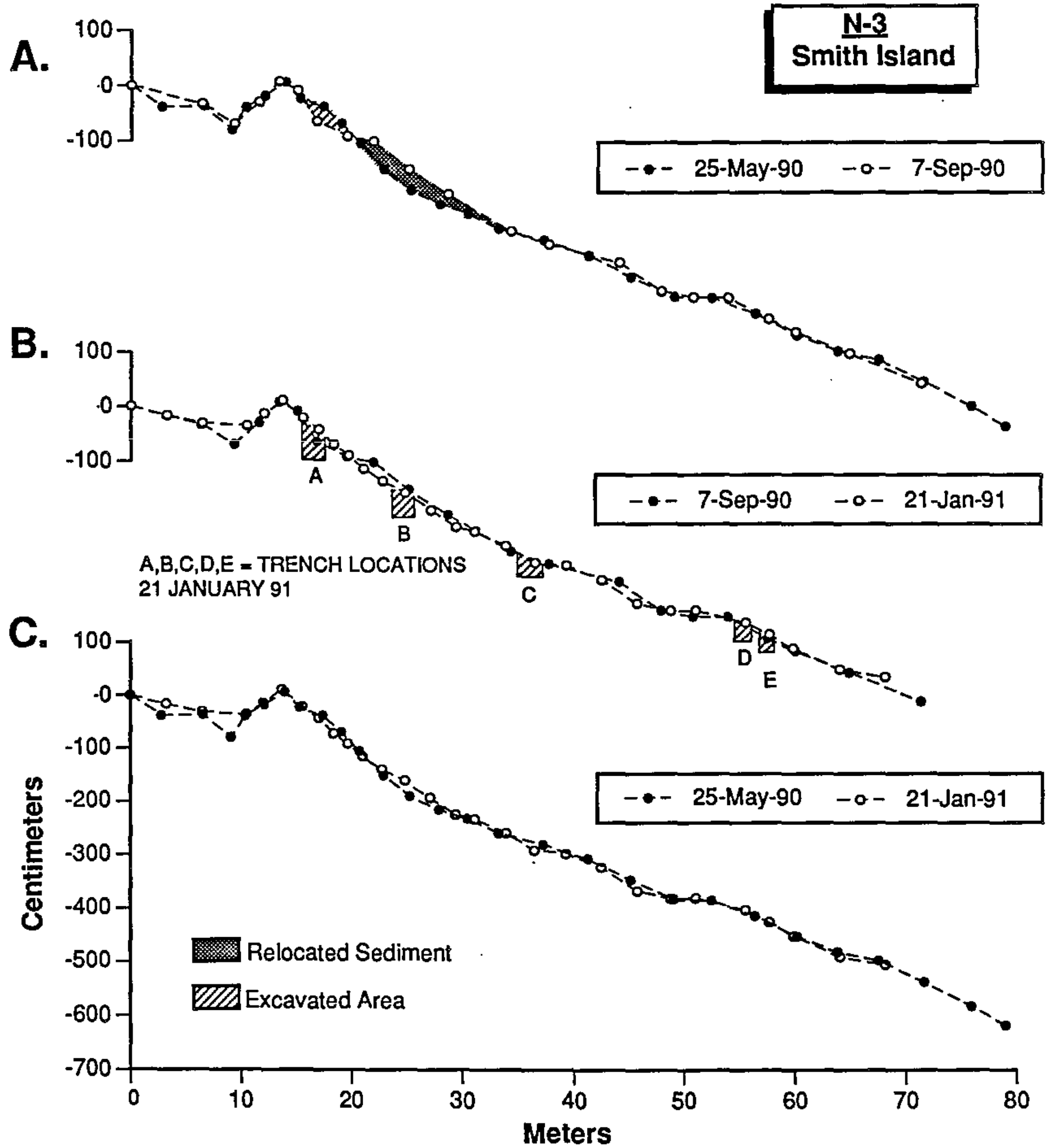


FIGURE 3. Changes at station N-3.

A. (25 May 1990 and 7 September 1990) Note that the excavated sediment had not been reworked by waves.

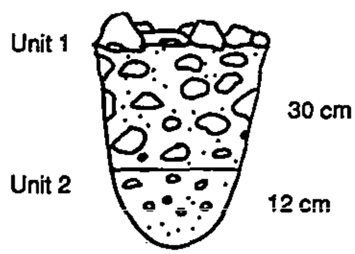
B. (7 September 1990 and 21 January 1991) The profile had recovered to near its original configuration. The location of the trenches dug on 31 January 1991 is given.

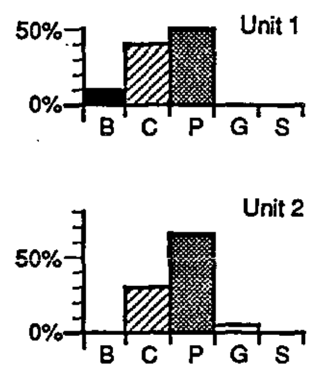
C. (25 May 1990 and 21 January 1991) Note the near overlap of the crest of the active storm berm after recovery of the relocated sediments.

N-3 SMITH ISLAND, 21 JANUARY 1991

- Oiled Zone

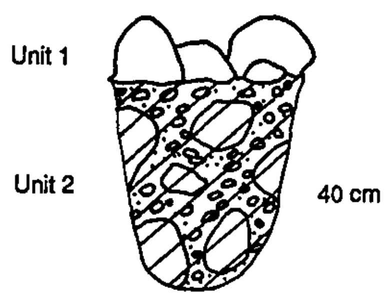
TRENCH A

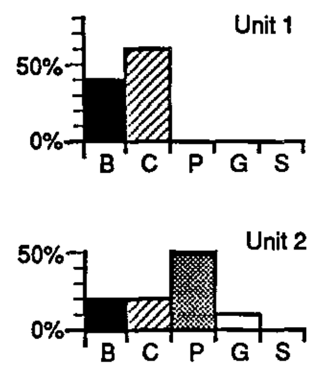




- Angular to subangular clasts, poorly sorted
- Coarsens upward
- Unit 1 clean, slight oil stain in unit 2

TRENCH B



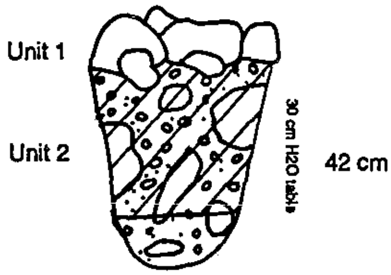


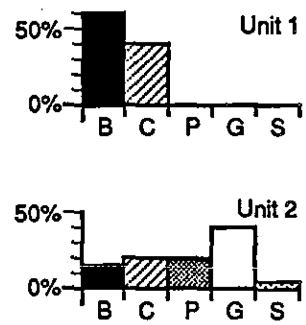
- Homogeneous material
- Subangular to subrounded clasts, poorly sorted
- Boulder armor on surface (unit 1)
- Medium oil stain in unit 2

FIGURE 4. Description of the four trenches dug at station N-3 on 31 January 1991 (see Fig. 3B for location). Note presence of subsurface oil under an armored surface in trenches B, C, and D, with heaviest oil in trench C.

N-3 SMITH ISLAND, 21 JANUARY 1991

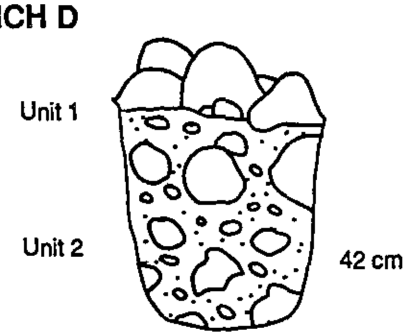
TRENCH C

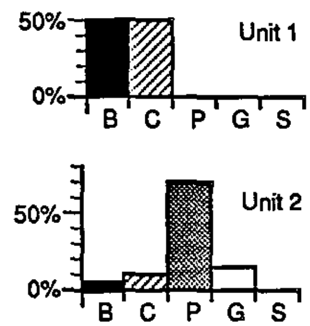




- Homogeneous material
- Subangular to subrounded clasts, poorly sorted
- Boulder armor on surface (unit 1)
- Black oil accumulated on water table

TRENCH D





- Homogeneous material
- Subangular to subrounded clasts, poorly sorted
- Boulder armor on surface (unit 1)
- Medium oil stain in unit 2

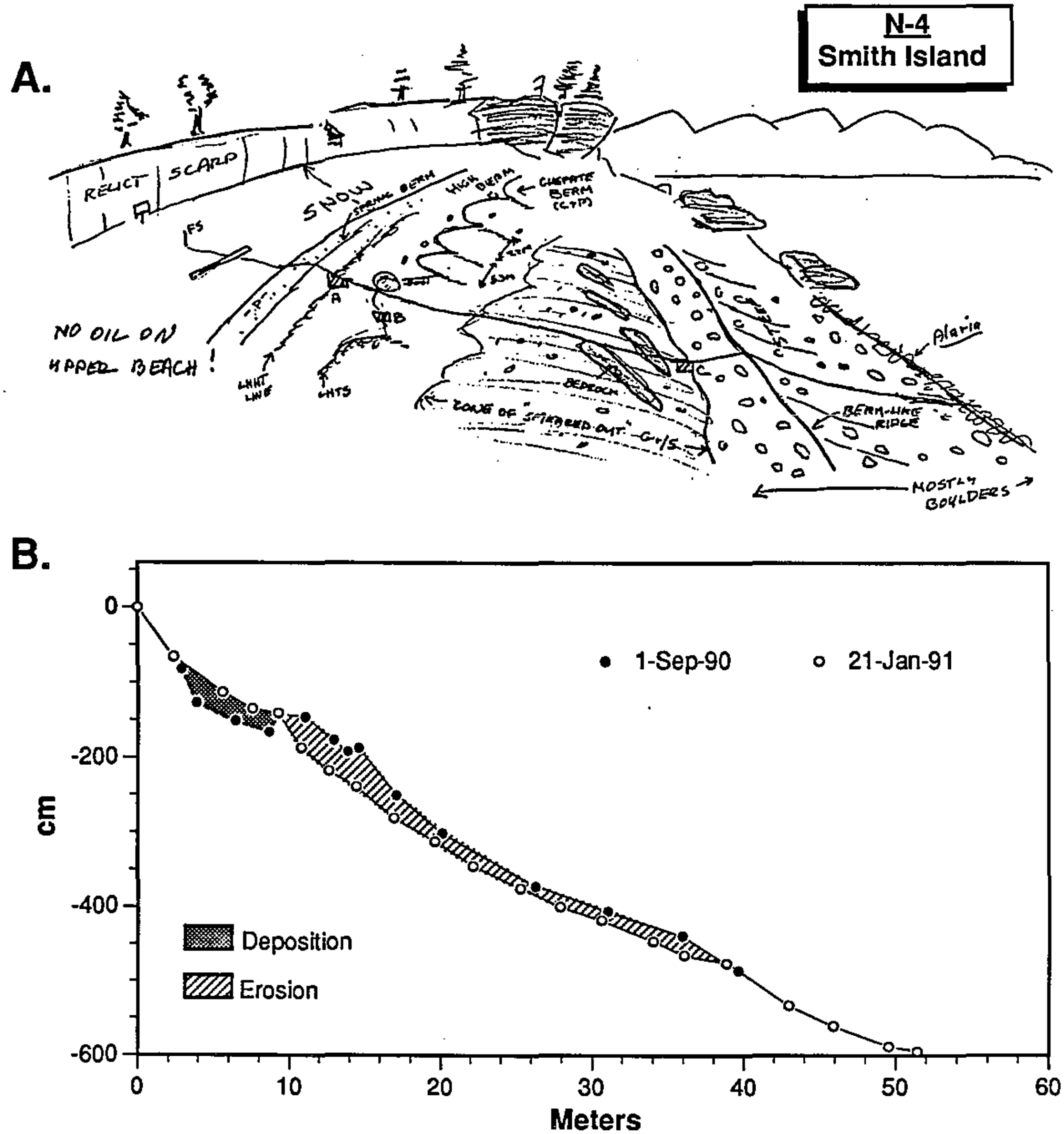


FIGURE 5. Station N-4.

A. Field sketch of station N-4 on 21 January 1991. Note exposure of bedrock outcrops along the middle of the profile.

B. Profile plots for 1 September 1990 and 21 January 1991. Note excavated zone and relocated sediment on the September profile. By 21 January, the excavation had been filled in and a normal beach profile restored. The sediment lost from the beach is believed to have migrated west to form the high berm shown in A.

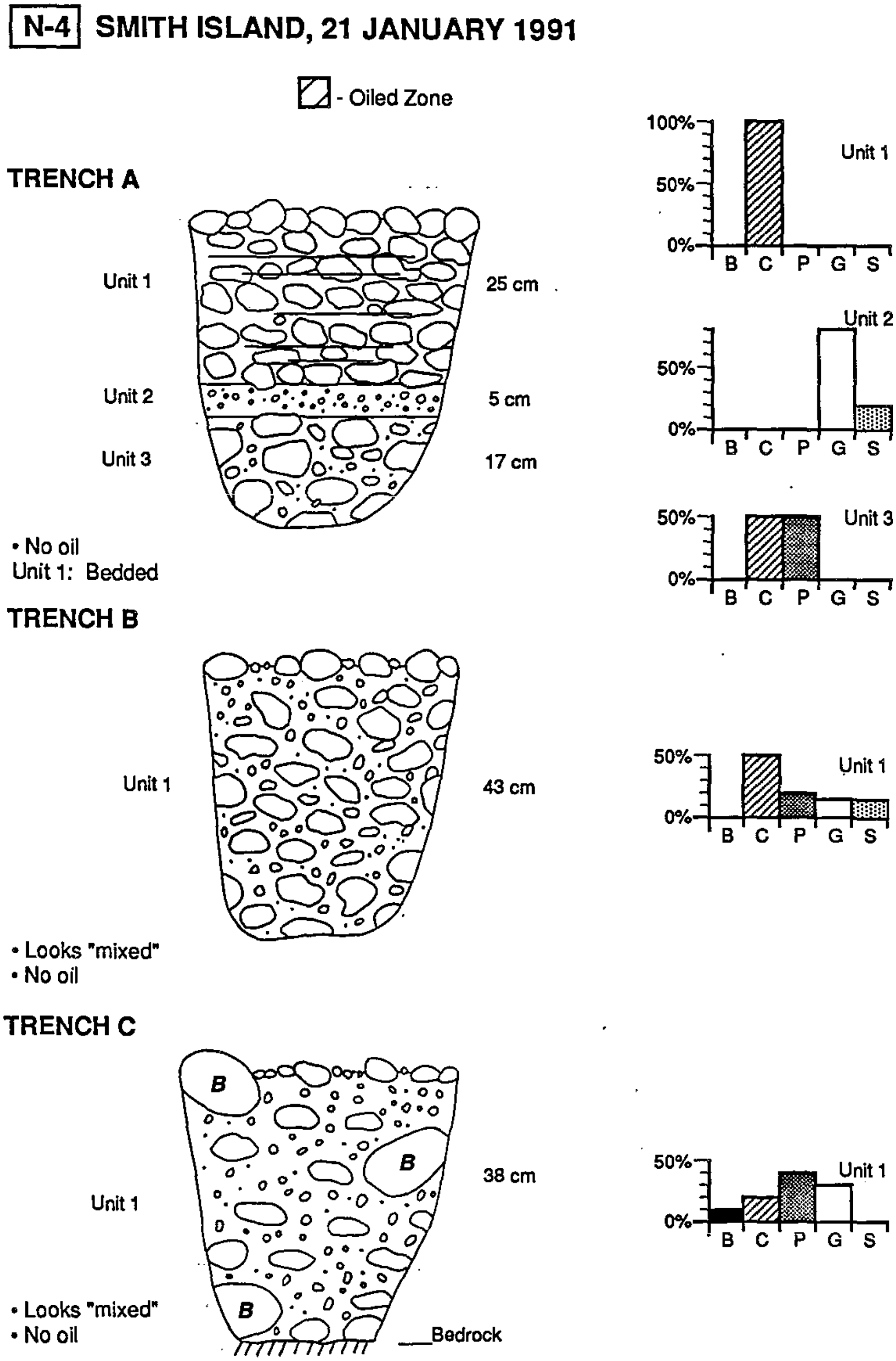


FIGURE 6. Trenches dug on profile N-4 on 21 January 1991. Note lack of bedding in trenches B and C, a result of the berm relocation, as well as the lack of subsurface oil.

As seen by the field sketch and profile plot in Figure 5, the profile at station N-4, which had been relocated in July 1990, had returned to a normal beach configuration by the time of the survey on 21 January 1991. However, there was some loss of sediment from the profile (Fig. 5B); these sediments apparently moved in a westerly direction, judging by the buildup of a large, high berm to the west of the profile (Fig. 5A). No surface oil was seen, and no subsurface oil was present in the trenches, even at the high-tide berms. The trenches dug on the profile are illustrated in Figure 6.

We believe the major contrast in the capacity of the beaches at stations N-3 and N-4 to retain subsurface oil, even though they have a similar exposure to wave action, is a function of the facts that:

1. The sediment veneer over the raised shore platform is thicker and coarser at N-3; and
2. The upper platform of station N-4 is somewhat steeper (6° as opposed to 4°).

Both of these factors enhance hydraulic flushing at station N-4 relative to N-3. Also, it is probable that waves abrade all the way to bedrock along much of the beach at station N-4 during storms.

Perry Island

Station N-17 on Perry Island, another berm relocation site, had returned to a normal profile configuration by 20 January 1991 (Fig. 7A). Relocated sediments appeared to be clean, and the subsurface oil in the intertidal zone was unchanged (i.e., low levels of TPH concentrations; some light cover and stain). Oil appeared to be mostly associated with the abundant organic material in the beach, thus TPH levels were 1,540 mg/kg in the berm area. The upper and lower platforms at this site are also relatively steep, 6° and 5° respectively, and the profile is subjected to large amounts of ground-water flushing.

Latouche Island

At the center of the beach at station N-15, the berm did not rebuild; the berm was lowered as a result of berm relocation (Fig. 7B). However, this sediment may have been partially transported south. The armor has not been re-established, although there is a single cobble layer on the upper platform. Surface oil occurred as a 0-15 percent coverage of an oil coat. Subsurface oil was greatly reduced, but remained as a light-to-moderate coating on all clasts (compared to the pre-berm relocation distribution as a layer of heavily oiled pebbles/granules below the cobble armor).

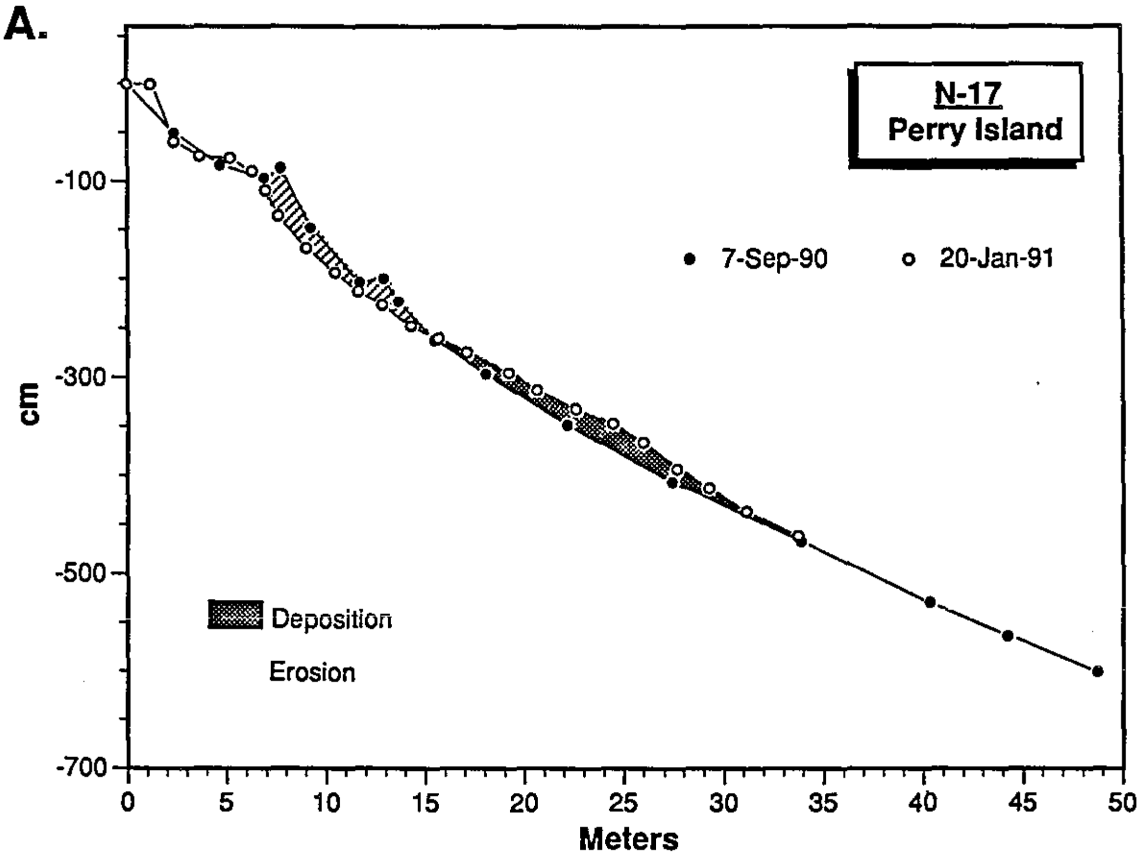
Knight Island

No significant changes occurred at NOAA's station N-7, as can be seen by the profile plots in Figure 8. Also, little change in the subsurface oil was observed on this well-armored cobble platform (see trench descriptions in Fig. 9 and Table 2). In fact, the highest TPH values observed at this station was the 18,000 mg/kg from the upper platform at 25-35 cm depth in January 1991. The GC/MS data show only slight weathering of the medium-weight polynuclear aromatic compounds.

Two berm relocation sites, KN209A and KN209D, both of which are located on the northeast portion of the next headland north of station N-7 (Fig. 1), were also surveyed. Both profiles had returned to normal topographic configurations. No surface oil was observed, except for scattered patties and broken pavement in the more sheltered areas and under large boulders. Subsurface oil was greatly reduced, but there was a zone of light-to-moderate "OR" in the intertidal zone. These profiles are given in Figures 10A and 10B.

Sphinx Island

A berm relocation site within SP-019A was examined but not surveyed. Very minor subsurface oil was observed at the high-tide berm (only a very small section of berm was relocated). There were multiple pebble/cobble berms, indicating active sediment movement.



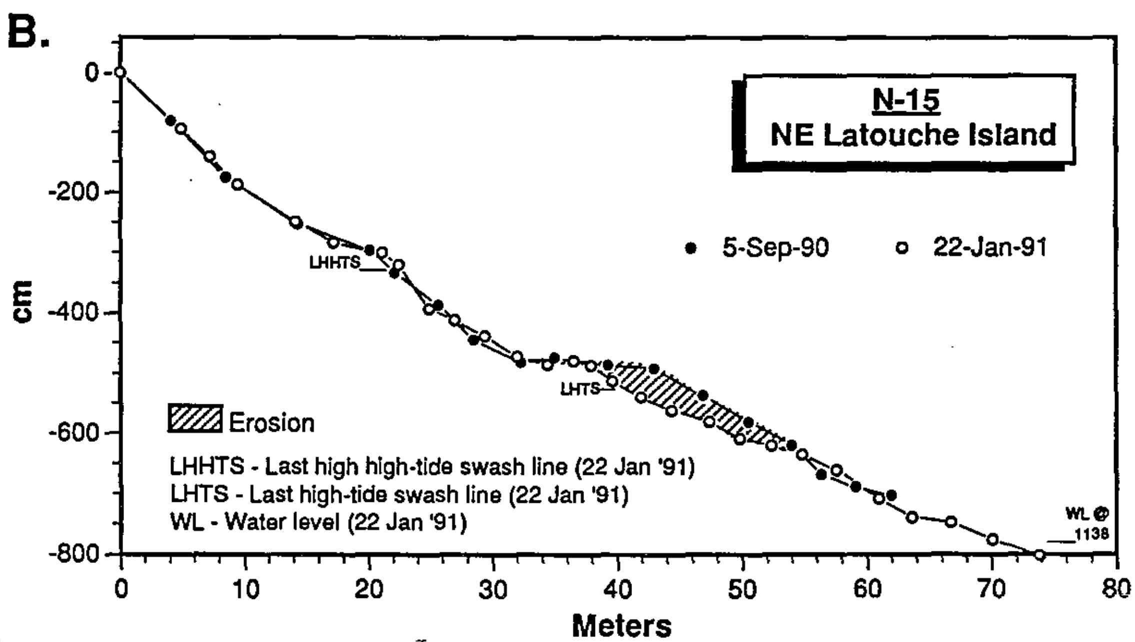


FIGURE 7. Profile changes at stations N-17 and N-15.

A. Station N-17 on 7 September 1990 and 20 January 1991. Note movement of sediment from the upper to the middle part of the beach.

B. Station N-15 on 5 September 1990 and 22 January 1991. Note loss of sediment from profile after berm relocation.

Synopsis of Cobble boulder Platforms with Berms

Most sketches in this category subject to berm relocation in the summer of 1990, the intertidal zones have returned to a topographically normal profile. Sediment has been variably redistributed; net erosion was seen in very few places. Nowhere has sediment totally returned to its original textural distribution. Subsurface oil in the storm/spring berms has decreased. There has been wide variation in the degree of change in subsurface oil in the intertidal zone to date, ranging from very little at stations N-3, N-7, and KN405A at Pt. Helen, to extensive at KN209A. Less change was seen where armor is well developed.

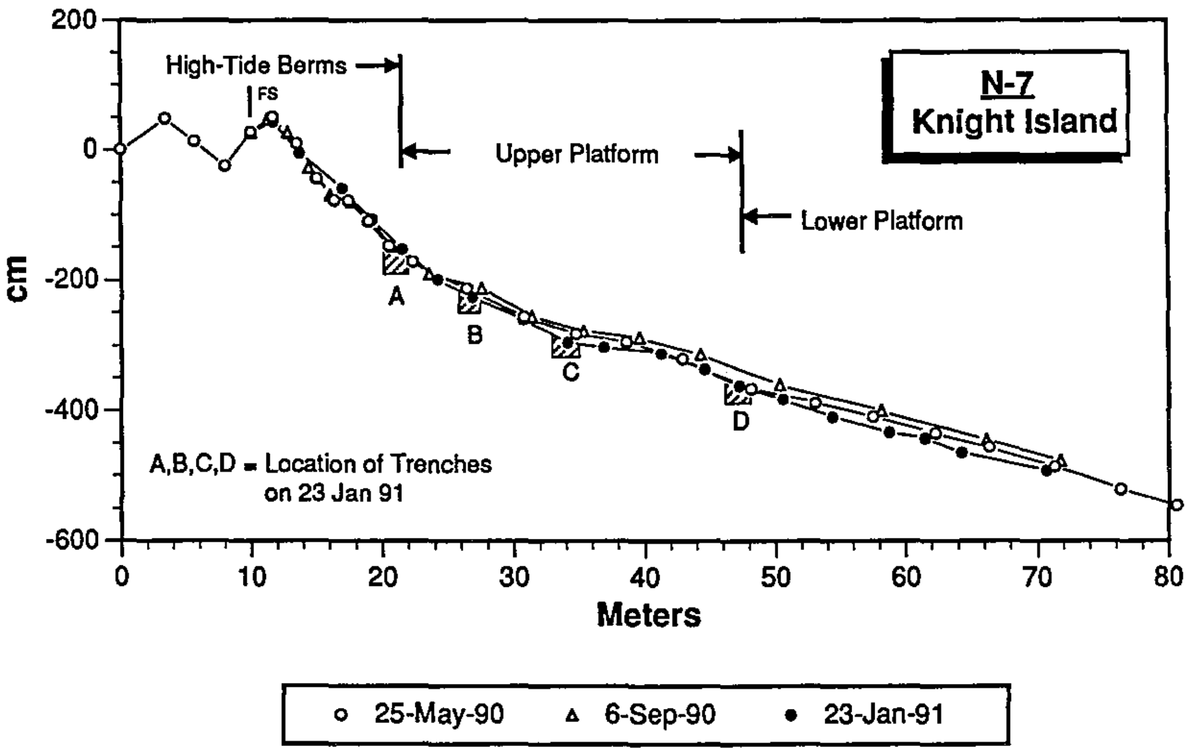
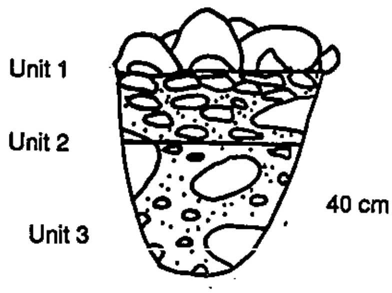


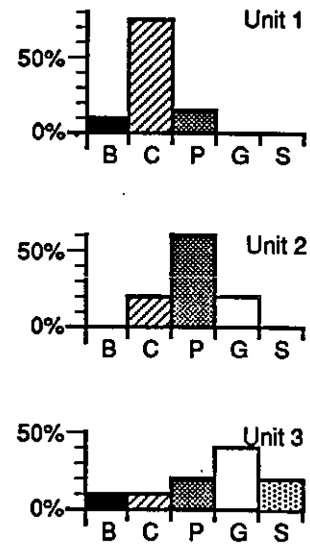
FIGURE 8. Surveys at station N-7 which illustrate the lack of change at this site.

N-7 KNIGHT ISLAND (NE), 23 JANUARY 1991

- Oiled Zone

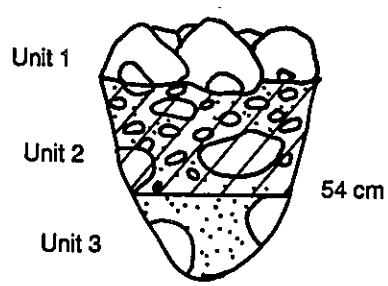
TRENCH A

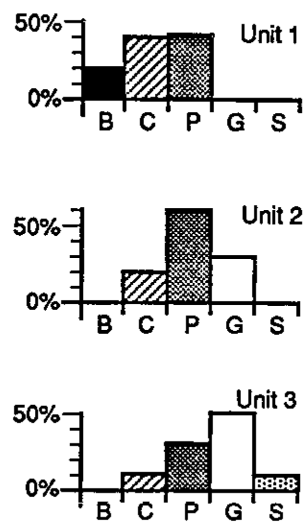




- Boulder - cobble armor
- Subangular to subrounded clasts
- Inversely graded
- Very light oil stain in unit 2, no oil in unit 1
- Light oil stain at top of unit 3
- Fine-grained organics (soil) in lower part of trench

TRENCH B





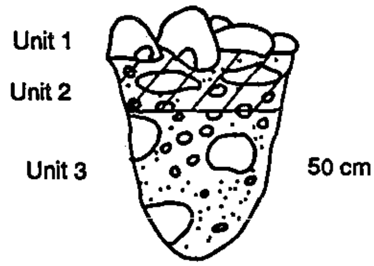
- Boulder - cobble armor
- Subangular to subrounded
- Medium oil stain in unit 2, clean in units 1 and 3
- Inversely graded
- Fine - grained organics (soil) in lower part of trench

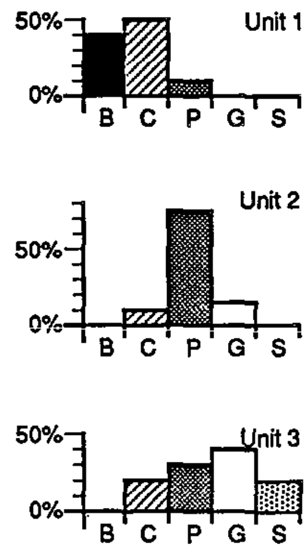
FIGURE 9. Description of the four trenches dug at station N-7 on 23 January 1991 (see Fig. 8 for location of trenches). Note presence of subsurface oil under surficial armor in trenches B and C.

N-7 KNIGHT ISLAND (NE), 23 JANUARY 1991

- Oiled Zone

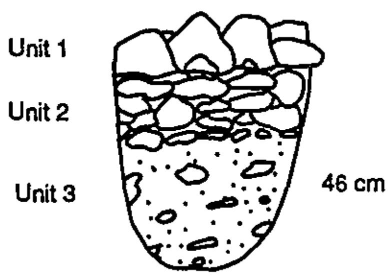
TRENCH C

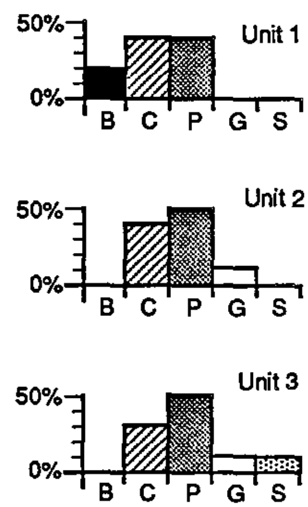




- Subangular to subrounded clasts
- Inversely graded
- Boulder armor
- Medium oil stain in unit 2
- No oil in units 1 and 3

TRENCH D





- Subangular to subrounded clasts
- Inversely graded
- Boulder armor
- No oil in unit 2
- No oil in units 1 and 3

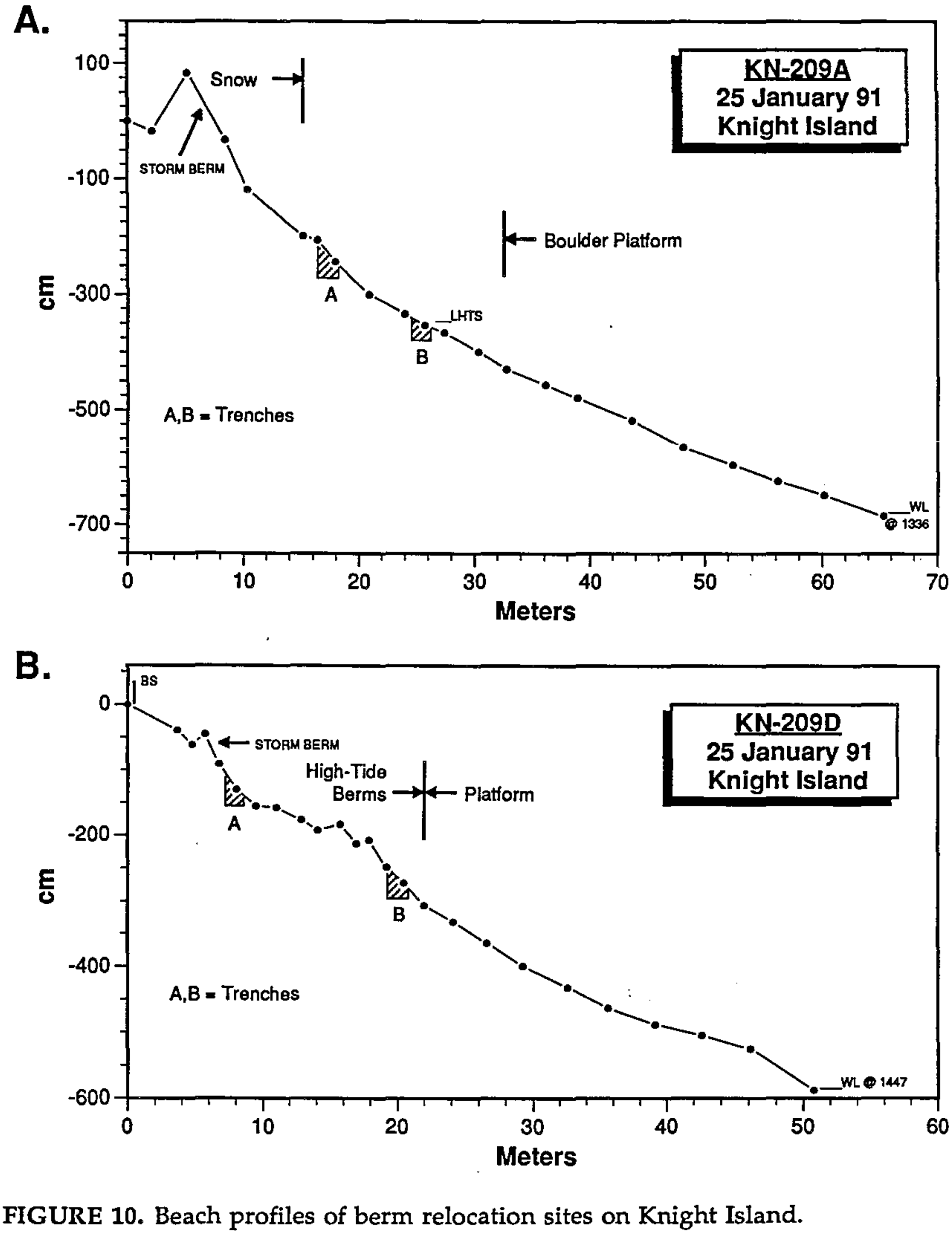


FIGURE 10. Beach profiles of berm relocation sites on Knight Island.

A. Profile KN209A on 25 January 1991. Note extremely large storm berm and raised boulder platform.

B. Profile KN209D on 25 January 1991. Multiple berms had developed at the high-tide line.

BAYHEAD BEACHES

Introduction

The heads of several bays at the spill site were filled with oil during the spill and were consequently subjected to extensive cleanup activities. Two of the permanent NOAA stations, N-18 and N-14, which occur at the heads of Sleepy Bay and the West Arm of Northwest Bay, respectively, fit into this category. Both of these stations contain mobile, fine gravel sediments and are close to anadromous streams. Three of the berm relocation sites visited in January 1991 are also beaches of this type.

Results of Surveys

Station N-14. There were no obvious changes in the profile, except where the low-tide ridge moved about 1 meter since May. The asphalt pavement is completely gone. Scattered patties were observed in the lower intertidal zone.

Station N-18. The stream channel has migrated approximately 50 m to the east (it now crosses the profile line, as shown in Fig. 11). The surface was erosional; it appeared to have been lowered 10-20 cm on the average. Subsurface oil remained unchanged; erosion has exposed the oil (see sketch in Fig. 11A). Subsurface oil was present in all of the trenches dug, as shown in Figure 12. A sample from a depth of 30 cm in trench B contained 34,900 mg/kg oil, the highest ever measured at this station. Even the sample from 44 cm in trench A was the highest ever measured at the high-tide berm, with 17,600 mg/kg. But the edge of the oil was very sharp, and samples collected from trenches C and E were clean, with TPH levels <50 mg/kg at depths of 20-30 cm.

LA-20C. Only visual inspections were made of this area. It appeared to have a normal profile, and the surface was clean. A photograph of this site is given in Figure 13A. Two trenches were dug, in the upper berm and the mid-beach; no subsurface oil was observed to 30 cm in either trench.

EL-057A. The profile returned to normal at this berm relocation site (Fig. 14A). The pebble berm appeared only very lightly oiled, and the pebble veneer on the beachface was clean. Moderate oil was observed from 10-30+ cm in the intertidal zone. A sample from 10-15 cm from the mid-beachface contained 7,720 mg/kg TPH. The lower platform had 5-10 percent coverage of an oil coat.

EL-056C. The profile returned to normal shape (Fig. 14B). The pebble berm and upper beach was visually clean to a depth of 44 cm. The lower platform was clean to 37 cm, with heavy oil at 37-66+ cm in trench C and 8-38+ cm in trench D (see Fig. 14B for location of trenches). A photograph of the subsurface oil in trench C is shown in Figure 13B. A sample of this oiled layer collected at 65 cm depth contained 2,210 mg/kg TPH. However, GC/MS analysis showed that the oil was highly weathered, with no naphthalene compounds present at all. There was a heavy oil film on the lower platform.

Synopsis of Bayhead Beaches

These beaches had a highly variable sediment and oil distribution pattern. At the more exposed berm relocation sites, the profiles returned to a normal shape. The pebble berms were readily rebuilt and the subsurface oil levels in the berm were reduced to very low levels. In the intertidal zone, subsurface oil was reduced in approximately the top 10 cm, but below this zone, subsurface oil concentrations appeared unchanged. At the more sheltered parts of the beaches (i.e., east of the stream at Sleepy Bay), there was no reworking of subsurface oil in the intertidal zone.

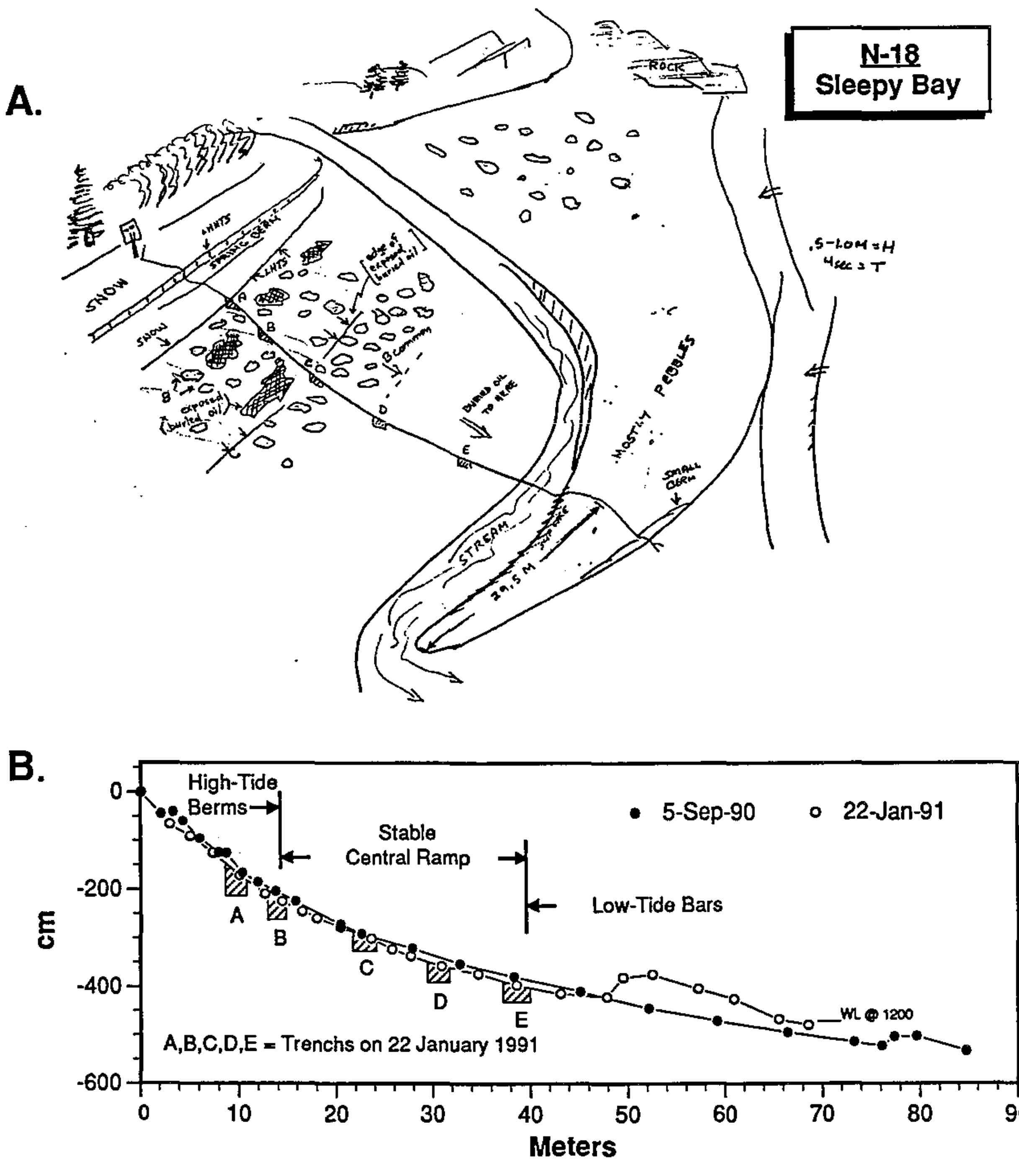


FIGURE 11. Station N-18 at the head of Sleepy Bay.

A. Field sketch of station on 22 January 1991.

B. Beach profile run on 5 September 1990 and 22 January 1991. The large bar developed on the lower part of the profile as the result of the migration of the stream mouth to the east on the order of 50 m.

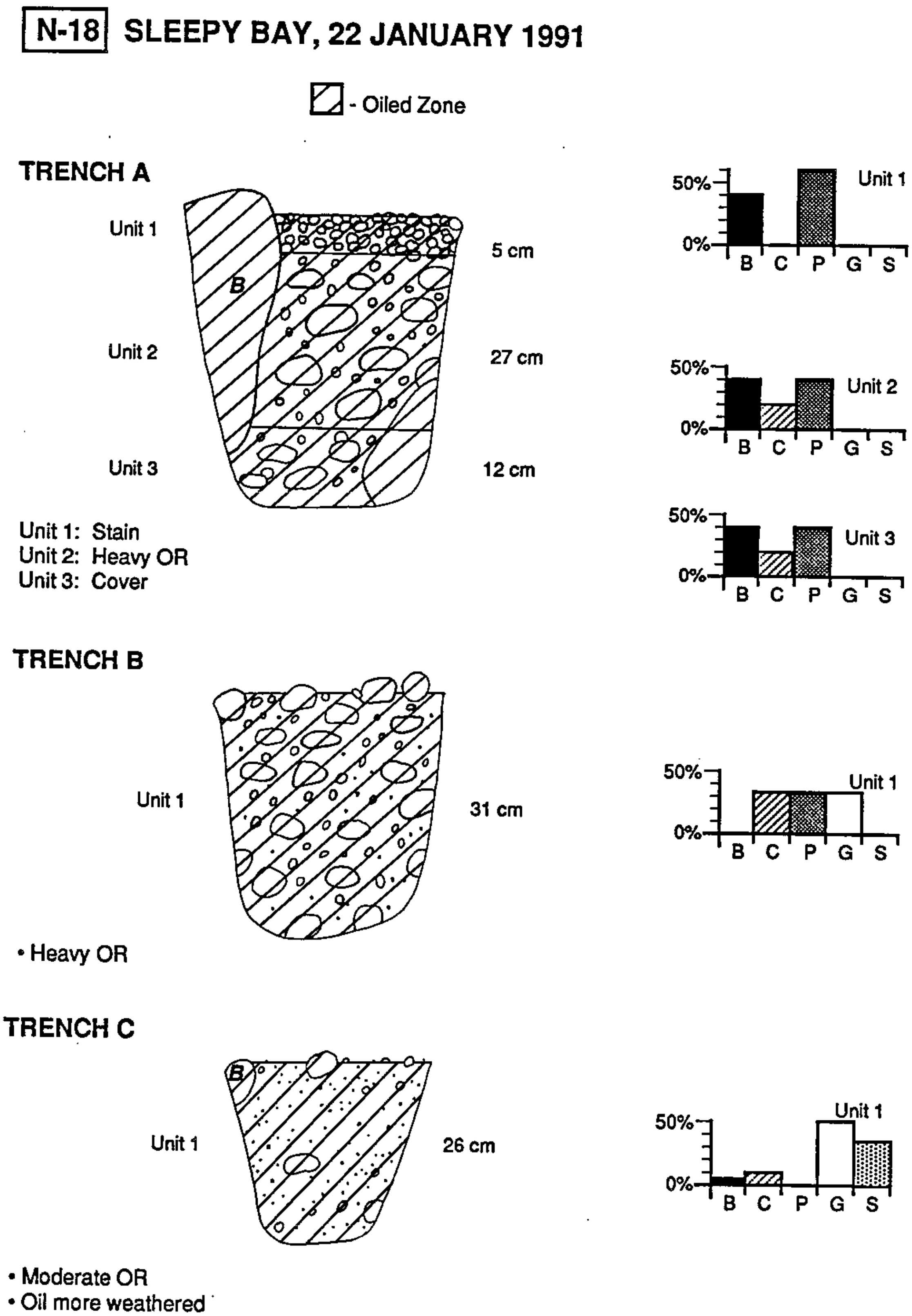
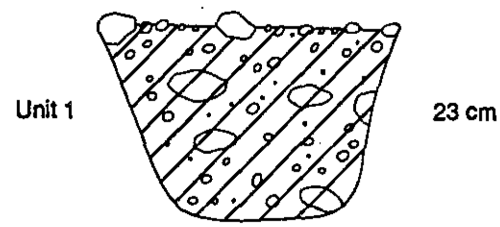


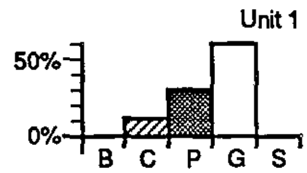
FIGURE 12. Description of the five trenches dug on profile N-18 (see Fig. 10 for location). Subsurface oil was present in all of the trenches.

N-18 SLEEPY BAY, 22 JANUARY 1991

- Oiled Zone

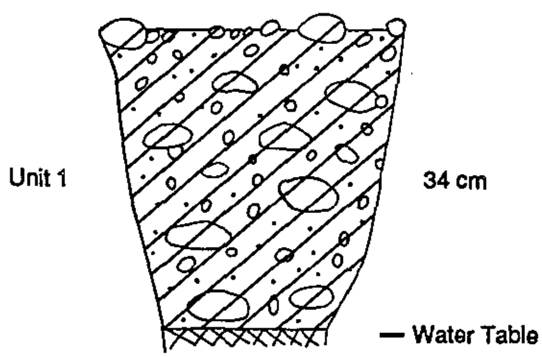
TRENCH D

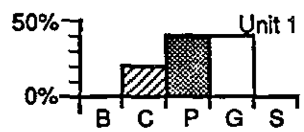




• No oil
Unit 1: Bedded

TRENCH E





• Light OR

FIGURE 13. (Facing Page)

A. The beach at LA-20C on 22 January 1991. The beach morphology had completely recovered from the effects of the berm-relocation activities of late summer 1990. This view looks northwest from near the position of Exxon's time-lapse camera.

B. Trench C at berm-relocation station EL-056C (see Fig. 14B for location). Note heavy oil at 37-66+ cm in the trench.

A.

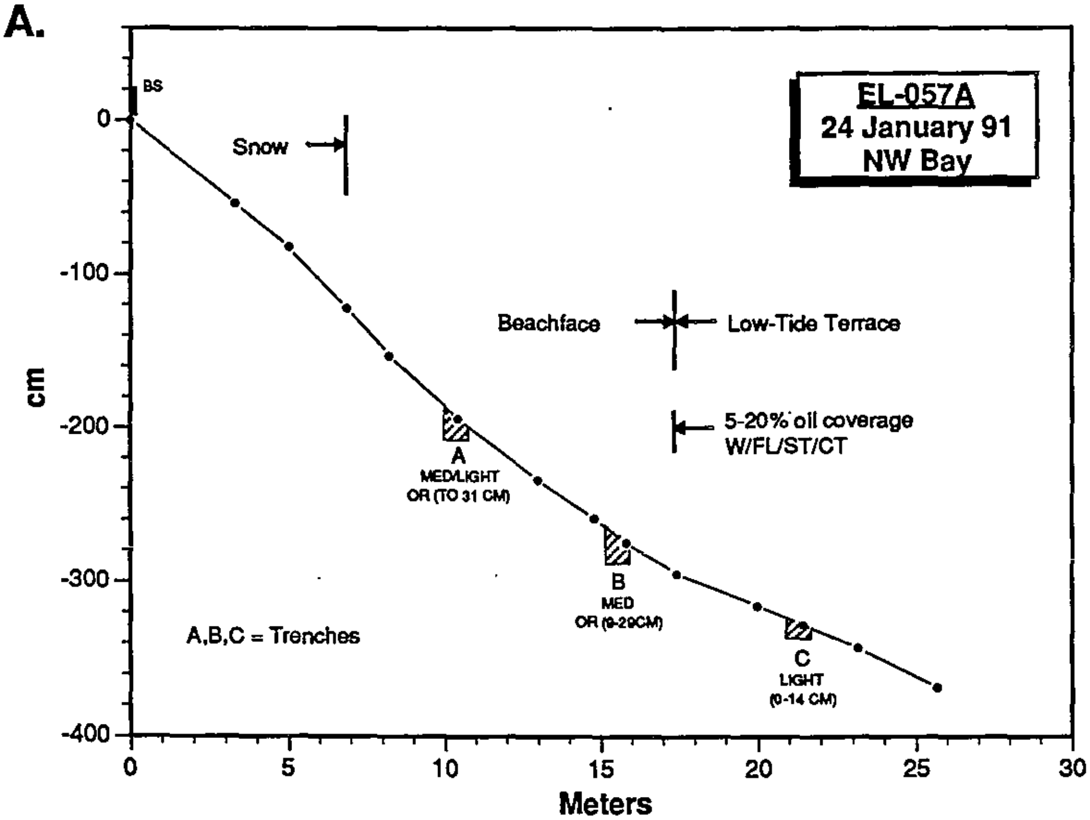
B.

FIGURE 14. (Facing Page) Beach profiles at berm relocation sites on Eleanor Island.

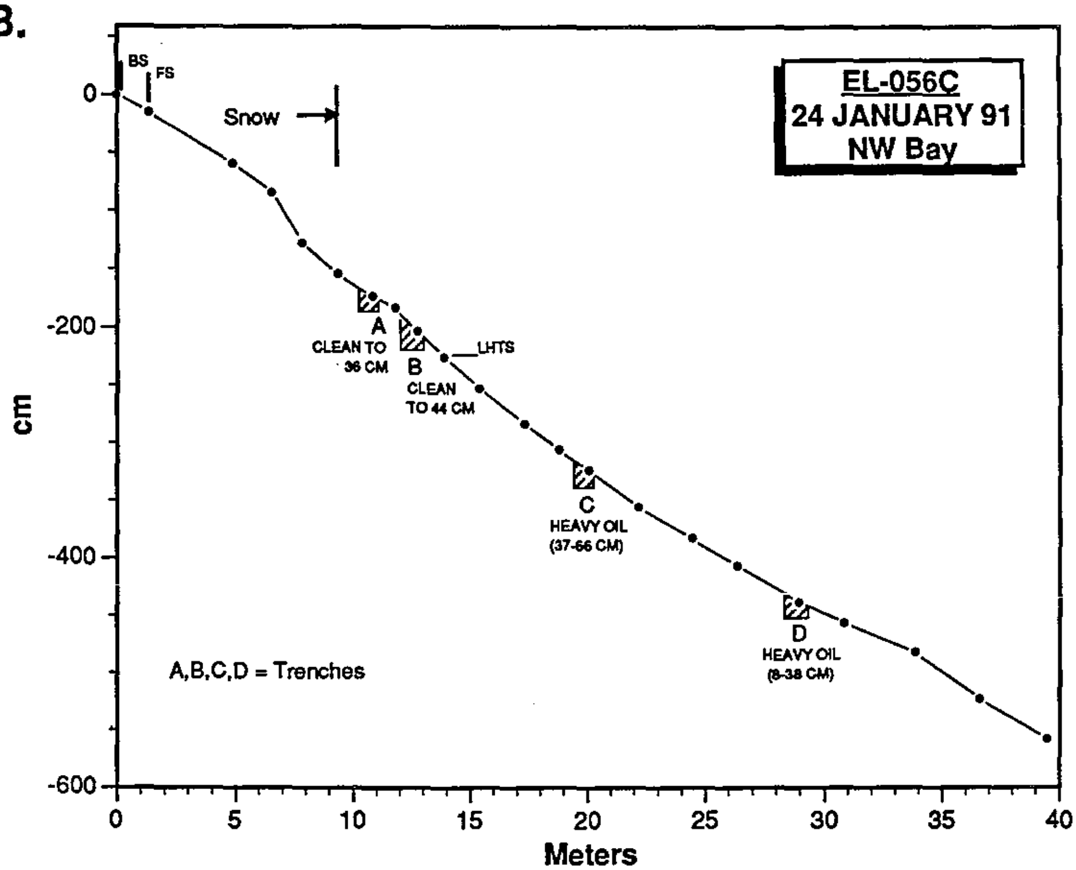
A. New profile at EL-057A, showing a smooth beach profile. Oil occurrence in trenches is also given.

B. New profile at EL-056C, which also was returned to a normal topography.

A.


EL-057A
24 January 91
NW Bay
BS
Snow
Beachface
Low-Tide Terrace
5-20% oil coverage
W/FL/ST/CT
A
MED/LIGHT
OR (TO 31 CM)
B
MED
OR (9-29CM)
C
LIGHT
(0-14 CM)
A,B,C = Trenches
cm
Meters
0
-100
-200
-300
-400
0
5
10
15
20
25
30

B.


EL-056C
24 JANUARY 91
NW Bay
BS
FS
Snow
A
CLEAN TO
36 CM
B
CLEAN
TO 44 CM
LHTS
C
HEAVY OIL
(37-66 CM)
D
HEAVY OIL
(8-38 CM)
A,B,C,D = Trenches
cm
Meters
0
-200
-400
-600
0
5
10
15
20
25
30
35
40

PEBBLE BEACHES WITH TIDAL FLATS

There were four stations that we visited that are in this category. NOAA stations N-11 on Crafton Island and N-9 on Block Island showed slight sheening in some of the trenches. There were very scattered patches of oil, as evidenced by a sample containing 9,920 kg/mg TPH collected at 0-5 cm from the upper beachface. However, both sites show definite improvement since the last surveys in the summer of 1990.

A profile located about 10 m north of NOAA station N-10, at KN-113A in Herring Bay, was surveyed for the first time (illustrated in Fig. 15). The profile at this berm relocation site had returned to a smooth surface. The stream mouth was closed off. The 14-cm thick oil layer at 62 cm in the lower beachface was unchanged from May 1990; this oil layer readily sheened. A sample from 60 cm depth contained 3,600 mg/kg TPH.

Another heavily reworked site visited is located at the first pocket beach south of NOAA's station N-9 on Block Island (EL-011A). The new profile, which is illustrated in Figure 16, had been returned to normal by wave action and the surface sediments were clean. The berm and upper beach sediments were clean with depth. The subsurface oil was moderate "OR" at depths of 23-43+ cm in the middle beachface and at 8-17 cm in the lower beachface. A sample from trench B at depths of 20-30 cm contained 8,500 mg/kg TPH and a sample from trench C at depths of 10-20 cm contained 21,900 mg/kg TPH. The subsurface oil occurred below clean sediments. Both of these stations, then, had oil several centimeters below clean overlying sediments.

A.

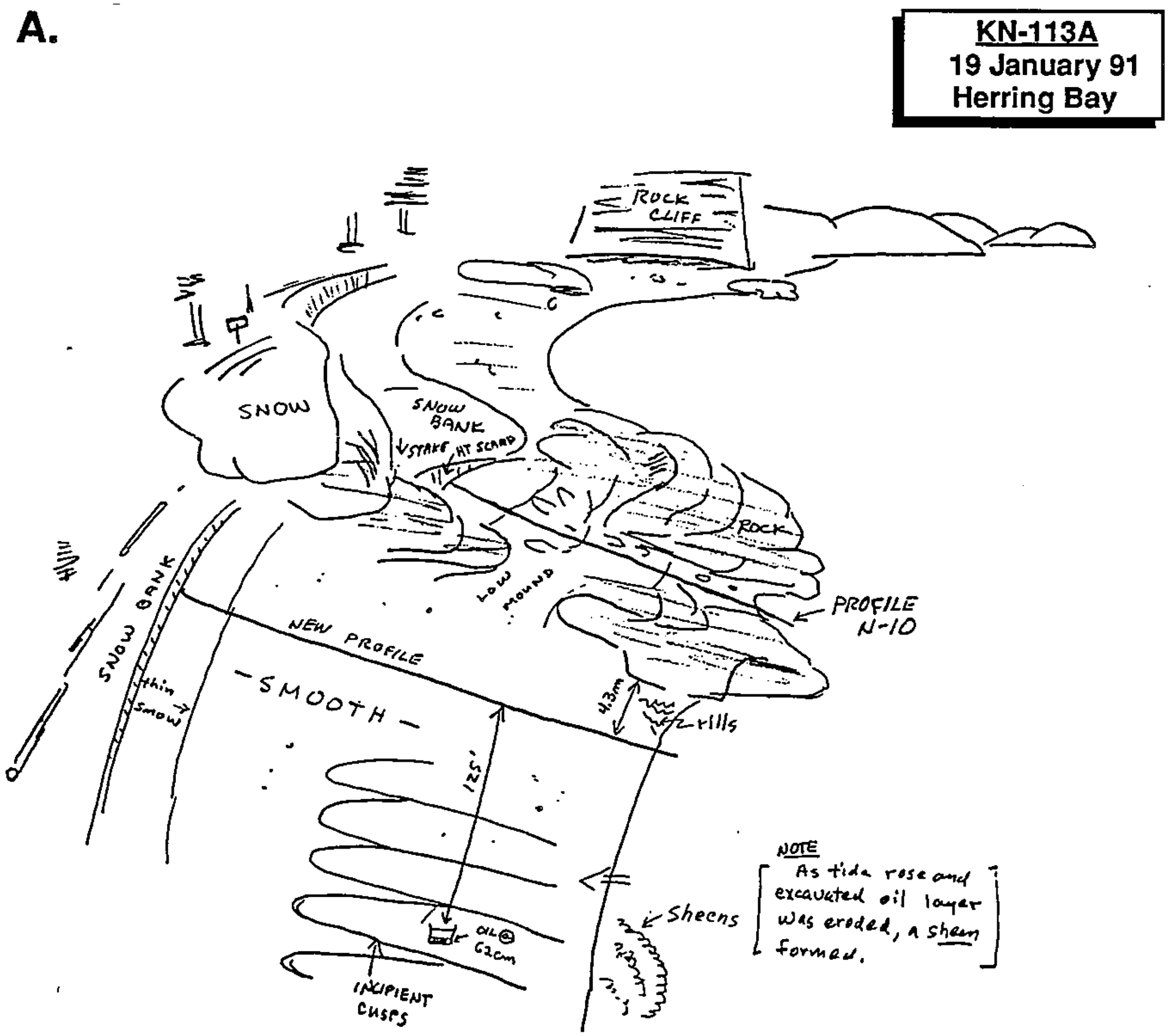
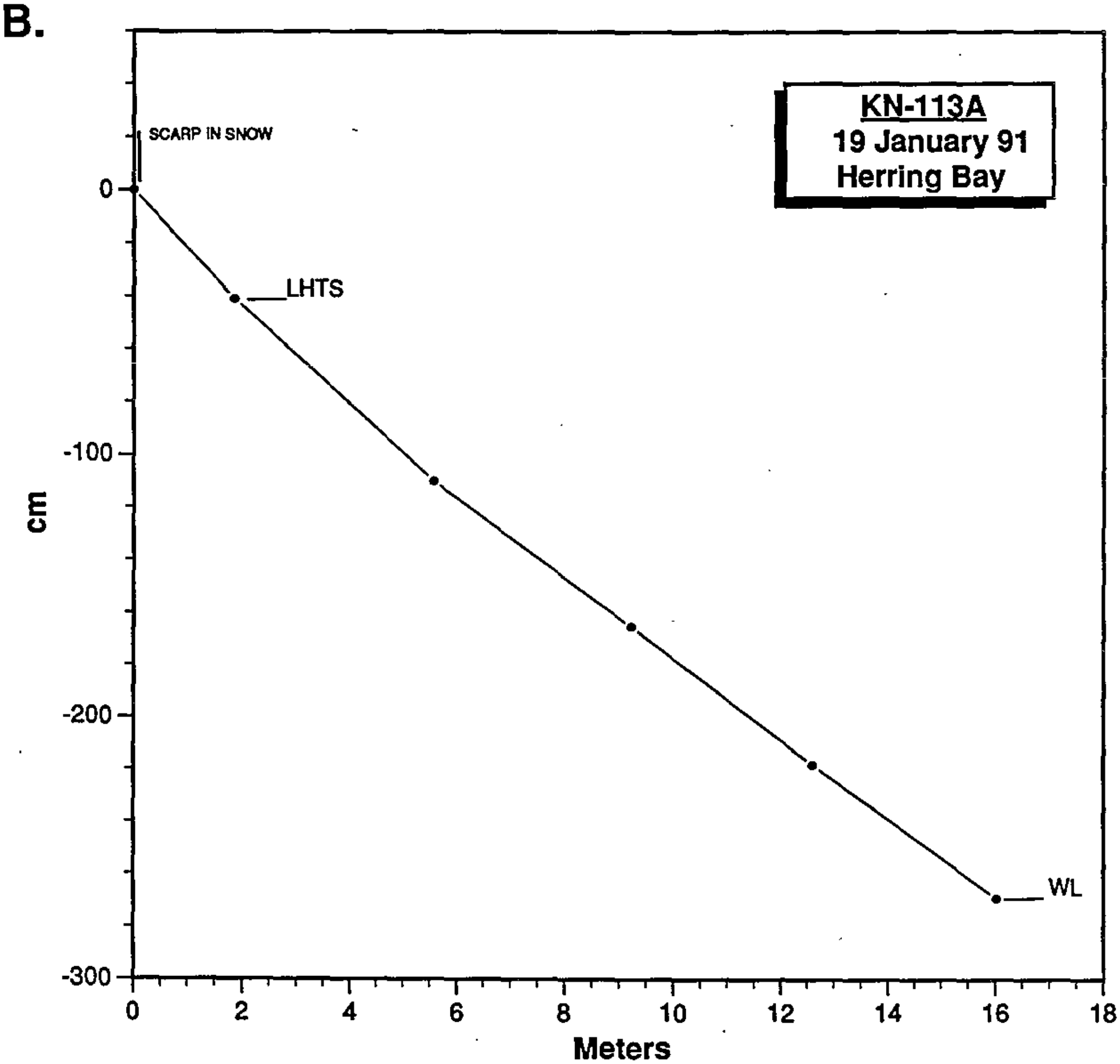


FIGURE 15. Berm relocation site KN-113 on 19 January 1991.

A. Field sketch. The recovered profile is becoming cuspate, a sign of normal, constructional beach processes.

B. Topographic profile of the smooth beach surface.

B.



KN-113A
19 January 91
Herring Bay
SCARP IN SNOW
LHTS
WL
0
-100
-200
-300
cm
0
2
4
6
8
10
12
14
16
18
Meters

A.

EL-011A
25 January 91
Block Island

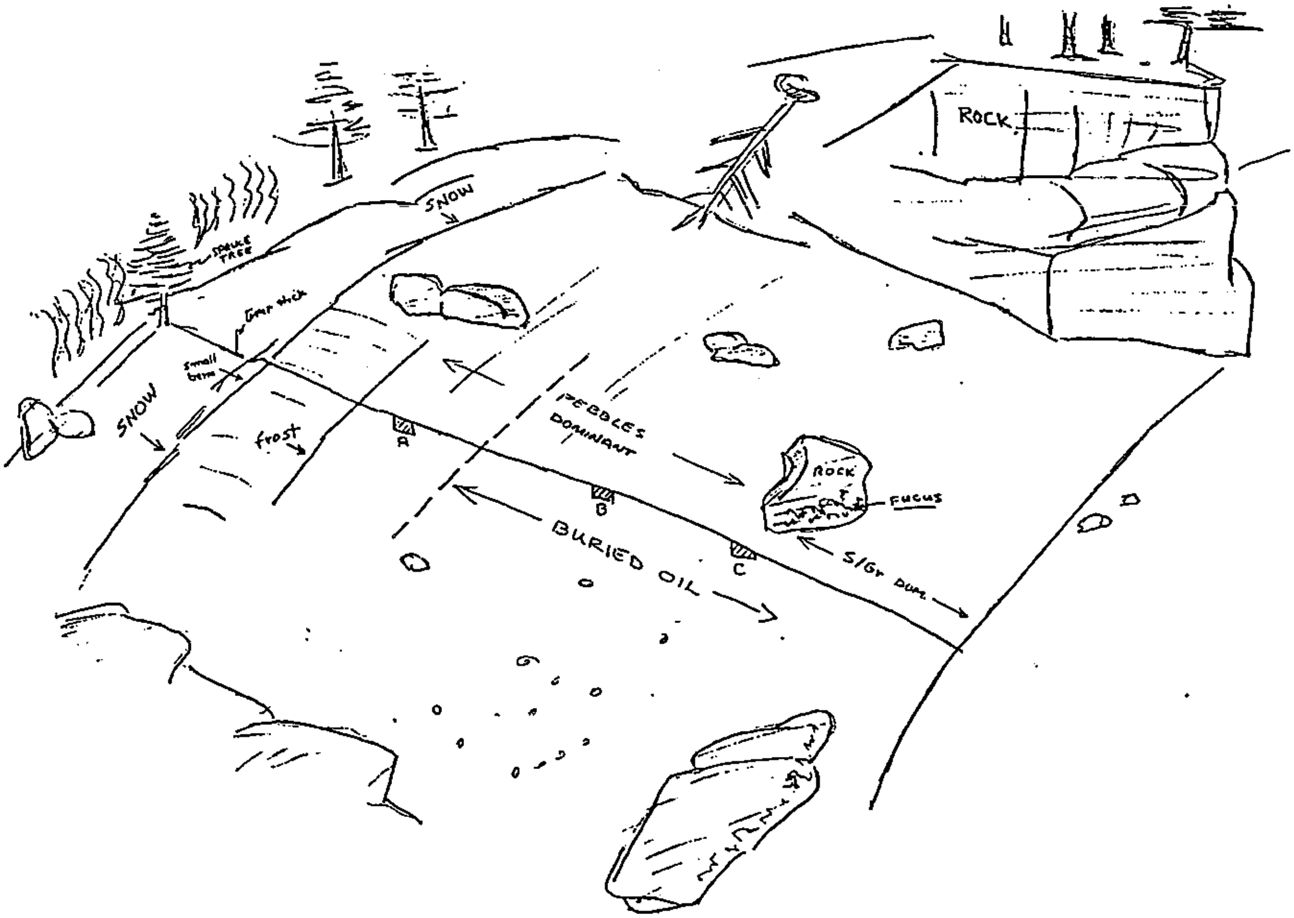
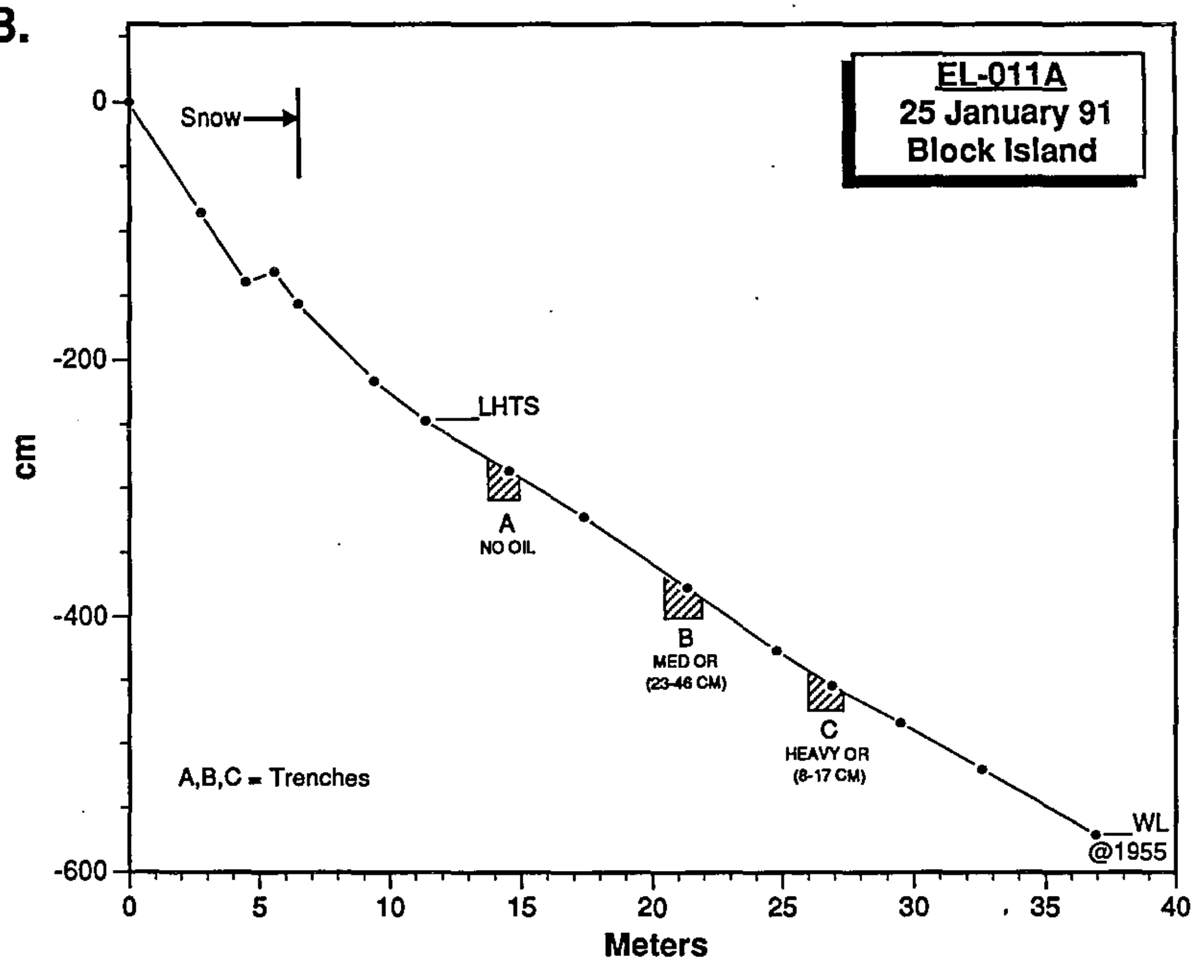


FIGURE 16. Berm relocation site EL-011A.

A. Field sketch showing location of subsurface oil.

B. Topographic profile, including location of trenches and nature of subsurface oil.

B.



EL-011A
25 January 91
Block Island
Snow
LHTS
A
NO OIL
B
MED OR
(23-46 CM)
C
HEAVY OR
(8-17 CM)
A,B,C = Trenches
WL
@1955
0
-200
-400
-600
cm
0
5
10
15
20
25
30
35
40
Meters

ROCKY RUBBLE SHORES

One site in this class, NOAA's station N-13 in Herring Bay, was visited. This set-aside station shows a continuation of the steady removal of surface oil that was observed in earlier surveys. The surface oil was down to 10 percent coat. No change was observed in the subsurface oil, which still occurred in significant amounts. A sample collected at 25 cm depth near the high-tide line contained 500 mg/kg TPH, whereas a sample at 10 cm depth near the base of the rubble slope contained 1,500 mg/kg. The GC/MS analysis showed that the oil in these subsurface sediments has weathered very little, retaining most of the methylated aromatic hydrocarbons. No tarmats or patties were seen.

COMMENTS ON TREATMENT IN 1991

It is clear from our observations that the major remaining question regarding treatment of the EXXON VALDEZ spill site is how to deal with the subsurface oil remaining in the various types of gravel beaches. Where oil remains in high-level berms, berm relocation similar to that carried out last year appears to be effective in removing the oil with minimal impact to the environment. Oil buried under armor on the platforms of some beaches presents a difficult problem. Overturning the armor and exposure ("tilling") of the oiled subsurface sediments is a mechanism that would surely allow most of the oil to be removed by wave action. Even beaches in the more sheltered bays, such as Northwest Bay, are readily returned to their normal topographic profile, because the sediments were mostly fine gravel. There may be also some loss of fine sediment from the beach before the armor is re-established.