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- 1b. Abundance (density/percent cover) of dominant species of epifauna does not differ significantly between pairs of site categories.
- 2a. Number and diversity of infaunal taxa in mixed-soft substrates do not differ significantly between pairs of site categories.
- 2b. Density of selected invertebrate species in mixed-soft substrates does not differ significantly between pairs of site categories.
- 3. Size structure and growth and mortality rates for selected mollusc populations (blue mussels, periwinkles, and drills) representing a range of feeding guilds (filter feeder, grazer, and predator, respectively) do not differ significantly among Category 1, 2, and 3 sites according to statistical comparisons of size structure.
- 4. Population characteristics of eelgrass in intertidal and shallow subtidal mixed-soft substrates do not differ significantly among unoiled (Category 1) and oiled (Category 2 and 3) sites on the basis of biomass, condition, and reproductive potential and success measures.

1.3.3 Study Area

Prince William Sound is a protected fjord system located on the southcentral coast of Alaska (Figure 1-1). Wave action from north Pacific storms is blocked by the outer ring of islands. The winds, however, are hardly abated by the low-lying peaks of those islands. This generates storm seas and chop that strike exposed shorelines with high intensity wave action during storm events. Within embayments, wave energy may be minimal despite high wind forces because of limited fetch and frequent shifts in wind direction (Bascom 1964). Tides are of the mixed semi-diurnal type, with a mean tide level of about 1.8 m and an extreme range of over 5 m.

The study area encompassed most of central and southern Prince William Sound from Sheep Bay on the eastern mainland to Eshamy Bay on the western mainland (Figure 1-1). The main sampling focus was, however, along the chain of islands stretching from Naked Island (in the central sound), south-southwest throughout the Knight Island group, to the islands protecting the southwest entrances to the sound. This portion of the sound lay in

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the path of movement of oil from the *Exxon Valdez* and many beaches in these islands received heavy oiling.

1.4 GENERAL DESCRIPTION OF INTERTIDAL COMMUNITIES IN PRINCE WILLIAM SOUND

Unoiiled beaches in Prince William Sound support biological communities that are relatively specific to and characteristic of a given habitat type and range of tidal elevation. Most beaches common to the sound have uppermost zones (above mean high water, MHW) that are typically devoid of significant attached macrobiota. Biota in these zones is subject to a great deal of stress due to infrequent salt water inundation, high freshwater exposure (during periods of rain), and extremes of temperature. An exception to the generally low biological productivity of this zone occurs on upper elevations of low-energy, silty gravel or sand beaches, where salt marsh plants (including grasses, sedges, and forbs), flourish.

At somewhat lower elevations, rocky substrates are dominated by barnacles (several species) and rockweed, with abundant littorine snails and limpets (*Lottiidae*) in and under the algal canopy. This level is referred to as the "upper *Fucus* zone." Bay mussels are usually present. At lower tide levels, in the vicinity of mean lower low water (MLLW), predators such as snails (*Nucella lima*, *N. lamellosa*, and *Searlesia dira*) and starfish (*Leptasterias* sp., *Derasterias*, *Evasterias troschelii*, and *Pisaster ochraceus*) reduce grazer populations, resulting in a rich growth of algae (including rockweed, filamentous greens, and several types of red algae). This area is referred to as the "lower *Fucus* zone."

Boulder/cobble beaches have many of the same species as the rocky area but have an added component of under-rock fauna, including shore crabs (*Hemigrapsus oregonensis*), hermit crabs (*Pagurus* spp.), and other small crustaceans, along with sea urchins (*Strongylocentronus droebachiensis*), snails, burrowing anemones (*Anthopleura artemisia*), polychaetes, and several species of eel-like fish (*Pholidae*, *Stichaeidae*). In low cobbles (e.g., below MLLW), larger kelps (*Laminaria* spp. and *Alaria* spp.) and several red algae become increasingly abundant. This community may be greatly reduced on cobble beaches exposed to high wave action, as this results in movement of substrate materials.

Soft intertidal habitats in Prince William Sound include relatively steep gravel, but more typically comprise a mixture of sand, gravel, shell, and some cobbles, with finer materials according to the energy regime (increasing silt with decreasing wave/current action). The

upper portions of "mixed-soft" intertidal substrates often have enough gravel or cobble to support the same primary species as the upper portions of rock and cobble beaches. Rockweed, barnacles, littorines, mussels, and limpets are the numerical dominants.

Epibiota at lower elevations is also dependent on the presence of hard substrates (such as gravel and cobbles) for attachment. Lower portions of soft beaches typically support a number of clam species (butter clams, littlenecks, and others), as well as naticid snails and sea stars, both of which feed on these clams. Additional infauna in the lower intertidal and subtidal eelgrass beds include a variety of polychaetes and several snails, crustaceans, and nemerteans.

Below MLLW, and in shallow subtidal zones, biota can be segregated into two rather distinct habitats: eelgrass beds in shallow areas with sand or mud substrates, and beds of large kelps with abundant red algae understory. This latter habitat supports a diverse fauna including juvenile rockfish, cods, juvenile shrimp, and several other fish and invertebrates.

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EXECUTIVE SUMMARY

GENERAL

A substantial amount of the crude oil which spilled from the tanker Exxon Valdez on March 24, 1989 was deposited on beaches in Prince William Sound. Major beach clean-up activities began in May and continued throughout the summer of 1989. Several hundred kilometers of shorelines were treated in the sound in 1989 using various manual hydraulic wash and bioremediation (fertilization) techniques; additional manual and mechanical clean-up and bioremediation treatments were applied during the summer of 1990. Significant concerns have been raised regarding the potential effects of these treatments on intertidal habitats and biota, especially those treatments using hot-water, high-pressure washes.

The overall objectives of the first year of this study were to evaluate intermediate-term (one-year) recovery of important littoral (intertidal and shallow subtidal) habitats from the effects of oiling and shoreline treatment, and to assess the influence of hot-water treatments on the nature and rates of recovery.

STUDY DESIGN AND APPROACH

Quantitative field surveys were conducted in Prince William Sound in July and September of 1990 to document environmental conditions in several types of habitats subjected to a variety of disturbances during 1989. Stratified-random sampling was used to assess epibiota and infauna at 28 intertidal sites representing several habitats and degrees of disturbance. Two to three stations were established at each site to represent intertidal elevations (zones) of biological interest. This sample design allowed for monitoring of long-term trends in recovery at sites of known oiling and treatment history. It is well suited (by the level of replicated sampling at each station) for comparisons at specific points in time between pairs of stations with similar habitats but different oiling and/or treatment histories. Because of the limited number of stations that could be sampled in each habitat/oiling/treatment category, and because these stations were not, strictly speaking, randomly chosen, it is less well suited to statistical inference regarding the generalized impacts of oiling and treatment over all areas with similar histories. Nevertheless, the degree of difference in some measured parameters was sufficient to draw some general conclusions regarding impacts.

Habitats of interest were productive rocky and mixed sand/gravel/cobble ("mixed-soft") beaches common in protected embayments, as well as high-energy boulder/cobble beaches. Previous studies in Prince William Sound had demonstrated that major intertidal assemblage dominants (both plants and animals) had survived 3-4 months in heavily oiled habitats. However, significant reductions (50 to 100 percent losses) occurred in all of these dominant species immediately following hot-water, high-pressure washing. Because of these identified adverse impacts, ecological effects of this type of treatment were a major focus for the present research effort.

Within each habitat type, these general categories of beaches were sampled: unoiled (controls or Category 1); oiled but not treated with hot-water washes (untreated or Category 2), and oiled and with high-pressure hot water (treated or Category 3). Information on initial oiling and on shoreline treatments applied at study sites was obtained from NOAA, state, and Exxon records, and personal communications with onsite personnel. Samples were collected for analyses of tissue hydrocarbon levels and population structure of several mollusc species, as well as for sediment hydrocarbons. Intertidal and subtidal eelgrass beds offshore of 10 locations representing all three site categories described above were sampled for growth, condition, and reproductive potential.

RESULTS

Cluster analyses determined that station treatment classifications based on chemical, epibiotic, and infaunal data matched the independently defined site categories derived from agency and Exxon records, and observations of field personnel. Sediment concentrations of polycyclic aromatic hydrocarbons (PAH) were significantly lower at unoiled control stations than at all oiled stations (untreated and treated), but there was no significant difference in mean PAH between untreated and treated stations. On the average, sediment PAH concentrations at untreated sites were highest at upper elevations while at treated sites, were highest at lower elevations. This suggests that intrusive treatment acted to move some hydrocarbons from the upper beach downslope; this pattern was not, however, statistically significant.

Tissue PAH in two grazing species (littorine snails and the blue mussel) showed positive relationships with site oiling and treatment histories (higher at untreated than at control and higher at treated than at untreated) while two predatory species (a drill and the sun star) did

not. PAH levels in predators were lower than in the primary consumers, indicating that biomagnification was not occurring in components of the food web examined.

Treatments applied in 1989 resulted in a range of effects on intertidal assemblages. Much of the variability apparently resulted from differences in the timing, nature, duration, and intensity of treatment. Effects of hot-water washing in 1989 remained evident at treated sites in 1990. Some treated rocky beaches contained remnants of abundant pre spill populations of barnacles, mussels, and rockweed; others were stripped to bare rock at mid and upper intertidal elevations and showed relatively little colonization by early fall of 1990. These beaches had significantly lower abundances of several community dominants such as rockweed, limpets, and littorine snails than did other oiled rocky beaches that received less severe or no treatment (i.e., untreated), or were not oiled (i.e., control). At sites falling into the latter two categories, community dominants were similar and significant colonization occurred in 1990.

Infauna on unoiled sand and gravel beaches was dominated numerically by polychaetes, bivalves, and crustaceans. Protected sand and gravel beaches were severely affected by high-pressure treatments which greatly altered beach morphology, regardless of water temperature. Finer sands and gravels were flushed from upper intertidal elevations, often burying the lower beach in several centimeters of sediment. This probably contributed to significant reductions in infauna (e.g., total abundance, diversity, and species richness in July, as well as densities of polychaetes and bivalves in both months) at treated beaches. In contrast, oiled but untreated sand and gravel beaches had a richer and more varied infauna, similar in most instances to that at unoiled control sites.

Examination of populations of three mollusc species (blue mussel, Sitka periwinkle, and a drill) suggests that these species may be experiencing some sublethal effects from oiling and/or treatment. Growth and mortality rates of the mussel and the periwinkle appeared to be affected adversely at oiled sites. The drill, an important predatory snail in the study area, apparently damaged by oiling and treatment, was not sufficiently abundant at untreated or treated sites to allow quantitative evaluation of population characteristics. The condition of molluscs, based on length/weight relationships, was generally poorer at treated and untreated sites than at control sites.

Several aspects of eelgrass biology appeared to be affected of oil contamination. Most important were rhizome/root biomass and density of flowering shoots, seeds, and young-

of-year plants. Rhizome/root biomass was higher at oiled sites. Density of each of the reproductive elements was highest at control sites and lowest at the oiled sites. It is significant that several of the more important differences indicated reduced reproductive potential at oiled sites as this could lead to long-term reductions in density and biomass of eelgrass beds, an important primary producer in many areas of the sound.

Additional analyses have not been completed at this time, including those for PAH levels in tissues from September collections. However, in comparisons of treated and untreated sites, the existing body of data suggests that high-pressure, hot-water treatment displaced some deposited oil from upper to lower intertidal and shallow subtidal elevations. This resulted in reduced abundances of dominant epiflora, epifauna, and infauna, including important hardshelled clams, delayed or depressed mollusc recruitment, depressed mollusc growth and survival rates, and possibly caused significant adverse effects on subtidal eelgrass beds. These conclusions are consistent with other study results reported in 1989 before and after hot-water treatments at two experimental sites in Prince William Sound.

CONCLUSIONS

The effects and extent of shoreline treatment in areas affected by the *Exxon Valdez* oil spill will greatly complicate assessment of the long-term impacts of treatment and the oil alone. Because much of the heavily oiled shoreline was washed with high-pressure hot water at least once, and because so little of the oiled shoreline was left untreated, only a limited number of areas remain where comparisons may be made to distinguish between effects of oiling and the effects of oiling plus treatment. Lack of specificity in the available treatment information (e.g., equipment, temperature, duration, bioremediation application rates, and repetitions) also complicates separation of effects of individual treatment approaches.

Nevertheless, the results from this study to date provide a strong basis to argue that conditions spanning a broad spectrum of biological properties reflect both the influences of hydrocarbon contamination and intrusive shoreline treatment. The high number of cases in which the null hypothesis of no impact from oiling and/or treatment was rejected is impressive. It is clear, based on the number of rejections and the high levels of significance observed in many cases, that the data provided by this study strongly support the conclusion that hydrocarbon contamination and high-pressure, hot-water treatment each caused major adverse impacts to the intertidal biota of western Prince William Sound, but that the effects of the treatment predominated. Moreover, it appears likely that the treatment, while



removing oil from the upper and mid-intertidal zone, where its effects were somewhat restricted to relatively tolerant organisms such as barnacles, rockweed, and mussels, transported the remobilized oil into the lower intertidal and shallow subtidal zones, where the oil was placed into contact with relatively more sensitive and productive organisms such as hardshelled clams and crustaceans.

CHANGES IN SHORELINE OILING CONDITIONS 1-1/2 YEARS AFTER THE 1989 PRINCE WILLIAM SOUND SPILL



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GLOSSARY

ASAP: August (1990) Shoreline Assessment Program.

Berm: A zone above the beachface that is nearly horizontal and is above the limit of normal wave action.

Bioremediation: Treatment of oiled surface and subsurface sediments by applying phosphorus and nitrogen fertilizer to enhance bacterial breakdown of petroleum.

Energy characterization: Shorelines in the Sound and Kenai-Kodiak are exposed to a variable range of wave energy, dependent on coastline configuration and available *fetch*. Three categories defined for this report are **exposed** (high), **moderately exposed** (moderate), and **sheltered** (low) wave-energy environments. High wave-energy shorelines are those open and exposed to long fetch areas. In general, high-energy shorelines in the Kenai-Kodiak region are subject to much more wave action than those in the Sound. Low wave-energy shorelines are those beaches that are sheltered, such as enclosed bays and inlets, with only very limited fetch areas. Kenai-Kodiak and Sound low wave-energy shorelines are of similar wave-energy exposure.

Fetch: The length of open water over which waves are generated by wind.

FASST: Fast Assessment Shoreline Survey Team ground survey carried out in February 1990.

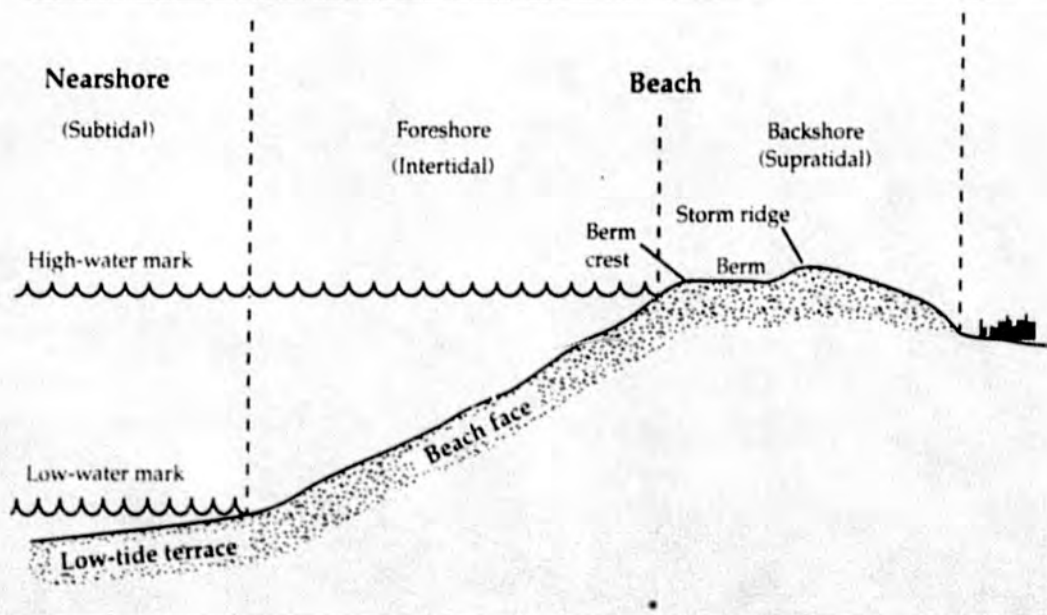
Gravel: Sediments that are a mixture of coarse sand and pebble-size material.

Gravimetric analysis: Determination of the concentration of a component (oil) in a mixture (sediment) obtained by extracting the component from a weighed aliquot of mixture, and then weighing the component.

High-water mark: The higher limit of the tidal water level. **Mean high-water mark** or the mean high-tide mark is the higher limit averaged over time. **Spring high-water mark** or spring high-tide mark is the higher limit of *spring tides*. **Neap high-water mark** is the higher limit of *neap tides*.

Beach Profile With Terminology

This figure shows shoreline terms used in this report.



Katabatic winds: Winds resulting when cold air masses at elevation flow downhill because of their greater density.

Neap tides: Tidal range is reduced when the gravitational pull of the sun is at right angles to, and thus opposing, the pull of the moon. These neap tides occur twice each month, during the first and last quarter of the moon.

Oil band category: Surface oiling was initially categorized by oil band width, where **heavy** oil cover is > 6 m wide; **moderate** oil cover is ≥ 3 m to < 6 m wide; **light** oil cover is < 3 m wide; and splashes are categorized as **very light**.

Oil conditions: Stranded oil was initially described by the following terms: **Length** is distance (m) alongshore, parallel to the waterline. **Width** is distance (m) normal, or perpendicular, to the waterline. **Thickness** is one of the following: **Pooled** is > 1 cm thick deposit; **cover** ranges between > 1 mm (0.1 cm) and < 1 cm; **coat** is < 1 mm, and can be rubbed off; and **stain** is < 1 mm, and cannot be rubbed off. **Range of subsurface oiled interval** is the depth interval of sediment matrix, within which oil is observed, measured from the local sediment surface, not from the tops of adjacent boulders or large cobbles protruding from the sediment.

Oil distribution: Surface oil cover is designated **continuous** where the surface oil covers 90 to 100 percent, **broken** where 50 to 89 percent, **patchy** or **sporadic** where 10 to 49 percent, and **splashes** (splatters or drips) where < 10 percent.

SCAT: Shoreline Cleanup Assessment Team(s) conducted the initial shoreline surveys during the spring and summer of 1989.

Sediment size: Units are defined by the mean diameter of the particles:

Boulder	> 256 mm
Cobble	64-256 mm
Pebble	4-64 mm
Granule	2-4 mm
Coarse sand	0.5-2 mm
Medium sand	0.25-0.5 mm
Fine sand	0.06-0.25 mm
Silt	< 0.06 mm

SSAT: Spring Shoreline Assessment Team survey in April 1990.

Spring tides: Tides that occur when the gravitational pulls of the sun and moon are in the same direction: thus, high tides are higher and low tides are lower than usual. Spring tides occur twice a month, at the new and full moon. The highest spring tides usually occur twice a year at the spring and autumn equinoxes when the sun is overhead at the equator.

Total extractable hydrocarbon (TEH): Concentration of hydrocarbon compounds in a sediment sample, determined for this study using gravimetric analysis.

Transect: A survey line along which regular observations are recorded. In this case, most transects run perpendicular to the shoreline.

SUMMARY

When the "Exxon Valdez" ran aground on March 24, 1989, it spilled approximately 258,000 barrels of oil on the waters of Prince William Sound. Within a few weeks, an extensive monitoring program was begun by Exxon to assess shoreline oiling conditions in the area. This report details that effort.

The long-term shoreline monitoring program was conducted from May 1989 to September 1990 at 28 sites in Prince William Sound and the Kenai-Kodiak region. The program was designed to provide information on changing oiled shoreline conditions that Exxon could use to decide on appropriate treatment activities.

A clear picture emerges of relatively rapid changes over the study period. There is a strong contrast between the heavily oiled study sites established in 1989 and the clean bedrock coasts and beaches that characterized most of the shoreline after the 1989-90 winter months. This contrast is documented by the monitoring program.

The monitoring program focused primarily on time-series observations of surface oil cover. This data set was supplemented by observations from other studies or surveys. All studies show that the 1989 treatment activities accelerated the natural cleaning, particularly of heavily oiled beaches. Study sites that were not extensively oiled also were cleaned rapidly, but largely as a result of natural processes. In sheltered areas, the treatment program flushed out most of the bulk oil in much the same way that waves and tides were able to wash exposed coasts. This bulk oil removal enabled weathering and degradation processes to progress more rapidly than would otherwise have occurred. On exposed coasts, wave abrasion and flushing were the predominant processes, whereas physico-chemical weathering and biodegradation were important following flush-and-flood treatment on sheltered coasts. The combined result of treatment and natural cleaning was that the majority of shorelines retained little or no oil by the end of the summer of 1990. Results of the study to date show the following:

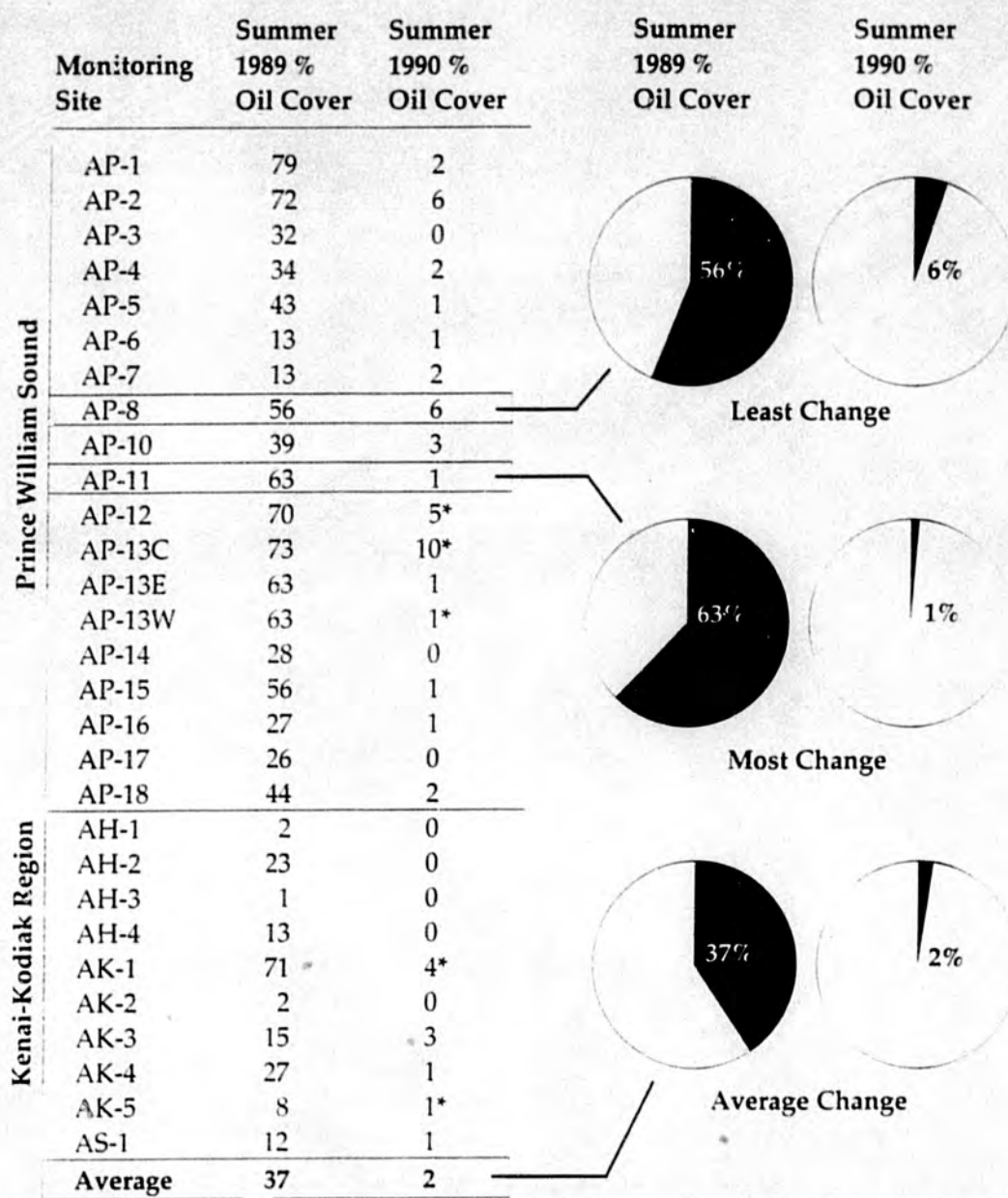
- The majority of the 28 study sites were initially heavily oiled, thus biasing the study toward worse-case conditions.
- By September 1990, 20 of 27 sites (one site was not revisited after August 1989) had an oil cover of 2 percent or less, and eight of these sites had no visible oil (Figure 1, on page 3).
- The combined average surface oil cover area of all the Prince William Sound study sites dropped drastically between May 1989 (six sites), from 46 percent of the total observed area to less than 2 percent by September 1990.
- The changes documented at the study sites resulted from a combination of Exxon's cleanup activities during the summers of 1989 and 1990 and the natural removal of oil by wave action and biophysical weathering. During the 1989 summer treatment

program, washing accelerated rates of natural cleaning by removing bulk oil. This activity enabled physical, chemical and biological degradation processes to proceed at faster rates than would have been possible with higher oil concentrations.

- Field data from the study sites show that oil cover reduction was generally proportional to the level of treatment (flushing) effort. A significant reduction in oil cover and amount of oil on the shoreline occurred during the summer of 1989 before the September survey.
- Rates of oil removal over the 18-month study period varied between sites because of a number of factors, including substrate character, available wave energy at the shoreline, and the treatment history of the site.
- Natural cleanup of the oiled shorelines occurred at rates that were faster than expected, particularly in sheltered, relatively low wave-energy environments. Oil removal at sheltered locations may be attributed to the interaction of fine sediment particles and seawater with the residual surface oil coating, to biodegradation, and to low levels of wave activity.
- Oil residues at the end of summer 1990 were generally limited to rock crevices or were beneath boulder or cobble sediments where neither wave action nor treatment activities had reached after 18 months. Subsurface oil remained at a few locations, where oil was able to penetrate into the large spaces between sediments. Bedrock accounts for an estimated 72 percent of the oiled coasts in Prince William Sound, and where oil did remain on the shores in September 1990, it was only in the form of surface patches. Beaches are predominantly gravel, and penetration on these beaches was limited to the top few centimeters by the presence of fine-grained sediments (sands).
- Oiled sediments that remained on the backshore of beaches in 1990 were mechanically relocated into the upper intertidal zone where available oil was removed and where oil residues could be reworked and cleaned by wave action.
- The effectiveness of the cleanup activities and natural recovery was shown in September 1990 by the small amounts of oil residue and the general lack of asphalt pavements, which typically form on heavily oiled, gravel beaches.
- Oiling conditions were found to be highly variable within a study site, and data analysis indicates that single transects may not always be representative of the overall distribution and character of oil on a beach.

Figure 1
Summary of Changes in Surface Oil Cover at Detailed Monitoring Sites

On average, surface oil for the monitoring sites reduced from 37 percent to 2 percent in about a year.



*Before berm relocation.

- Key organisms were observed to be similar in abundance and distribution on most oiled and non-oiled sites in September 1990.
- Ecological recovery appeared to be enhanced at some sites where 1989 treatment activities (flush and flood) were able to remove the majority of the bulk oil.

Several previous spills have occurred in similar coastal environments, for example, the "Arrow," "Metula," and "Nestucca" spills, and the Baffin Island Oil Spill (BIOS) experiment. Experience gained from these spills was of great assistance in evaluating oiling conditions in Prince William Sound and the Kenai-Kodiak region, but no other spill has been studied to the same degree as has this. As a result, a more accurate picture emerges of how and at what rates stranded oil is removed under varying coastal conditions.

INTRODUCTION

A site-specific, long-term monitoring program of shorelines oiled by the spill was initiated by Exxon in May 1989 and continued at regular intervals through the winter to the most recent survey in September 1990. Twenty-eight locations were staked during the spring and summer of 1989 and systematically document the changes in oil cover through time (Figure 1, on pages 6, 7 and 8). Monitoring sites were chosen from a list of heavily oiled sites in the Sound and Kenai-Kodiak region. Monitoring was conducted at monthly intervals from August 1989 to January 1990, and in March, June, and September 1990. Weather conditions affected the program, but 126 out of a possible 168 winter site visits were completed from September 1989 to March 1990.

This report summarizes the data collected from the site surveys through September 1990. The discussion is considered preliminary at this stage of interpretation. Though data reduction is still in progress, the trends and conclusions represent the conditions at the study sites and the changes that have occurred on these shorelines between April 1989 and September 1990. Additional information has been taken from a number of other related studies conducted by Exxon. These studies include:

- An initial shoreline assessment in the summer of 1989;
- A Fast Assessment Shoreline Survey Team (FASST) ground survey in February 1990 in the Sound;
- A Spring Shoreline Assessment Team (SSAT) multi-agency ground survey in April 1990;
- An August (1990) Shoreline Assessment Program (ASAP) multi-agency ground survey;
- A time-lapse photography program at five locations in the Sound conducted between November 1989 and April 1990; and
- A study of beaches where sediments were relocated from the backbeach to the upper intertidal zone during summer 1990.

Prince William Sound

The "Exxon Valdez" grounded on Bligh Reef on March 24, 1989, releasing approximately 258,000 barrels of North Slope crude oil on the waters of northern Prince William Sound. The Sound is a large inland sea with a complex coastline of irregular bays and passages (Figure 2, on page 6). This complexity results from the recent glaciation of this upland region. Tectonic uplift during the most recent (1964) major earthquake caused the emergence of shorelines throughout most of the Sound, with vertical changes on the order of 1 meter (m) in northwestern sections and of 3 m in the south on Montague Island (Plafker 1965). Many beaches, therefore, are young and may not have reached a dynamic equilibrium with wave conditions. The tidal range varies

from 3 m during neap tides to 6 m during spring tides. Waves are locally generated, as north Pacific swells have little effect beyond the narrow straits that connect the Sound to the ocean. Maximum fetch distances reach 100 kilometers (km) in the central, open area of the Sound, although they are generally less than 50 km. Wind velocities vary seasonally and are highest between October and March. The strongest winds are generally from easterly directions (Brower et al. 1988). The resulting wave climate is characterized by a relatively calm summer, and by winter storm events associated with low-pressure systems that pass through the region. Time-lapse photography over the 1989-1990 winter recorded breaker heights greater than 2 m on exposed coasts during storms, whereas in sheltered environments wave heights rarely exceeded 0.25 m.

Less than 20 percent of the shoreline of the Sound was oiled and the physical character of the coastal zone that was oiled is dominated by bedrock outcrops and poorly sorted sediment beaches. Bedrock outcrops form about 60 percent of the oiled shoreline in the Sound. Boulder-covered bedrock platforms represent nearly 12 percent and mixed cobble, pebble and sand beaches form about 28 percent. On exposed shorelines, the mixed sediment beaches commonly have a surface veneer, or armor, of coarse sediments (boulders and cobble) underlain by mixed gravel, sand, cobble, and boulders. Well-sorted cobble and boulder beaches occur on a few open-coast shorelines, but these are not common in the Sound. Fine-grained, well-sorted sediments (sand beaches, mud flats, or marsh depositional environments) are not common in the Sound of Prince William Sound. Stranded logs, however, are a common feature of the upper beach area on most shorelines.

Kenai-Kodiak Region

Oil was carried out of the Sound through the straits that connect the Sound to the Gulf of Alaska (Figure 2, on the next page). The anticlockwise coastal currents then moved the oil west and southwest along the coast of the Kenai Peninsula toward the Kodiak Island-Shelikof Strait region. The shorelines of the Kenai-Kodiak region are similar in many respects to those of Prince William Sound, except that wave-energy levels are considerably greater in Kenai-Kodiak. Open-ocean wave heights are greater than 4 m for approximately 15 percent of the time from October to April (Brower et al. 1988), and the contrast between high wave-energy, open-ocean shorelines and adjacent sheltered, low wave-energy environments is very marked. Fine-grained sediments are supplied to the area by rivers and by erosion, and sandy beaches occur at a few locations. The outer coast beaches are often formed of well-sorted sediments with high storm ridges.

Ice is not an important element of the coastal environment of the Sound or Kenai-Kodiak region, but where the tidewater glaciers reach the sea, ice is the shoreline. Sea ice forms locally at the heads of bays where the surface water is fresh or brackish and can freeze during mid-winter cold periods.

Figures 2, 3, and 4, on pages 6, 7, and 8, show general study areas in Prince William Sound and the Kenai-Kodiak region, plus specific site locations. Detailed maps are placed in Appendix A.

Figure 2
Regional Location Map

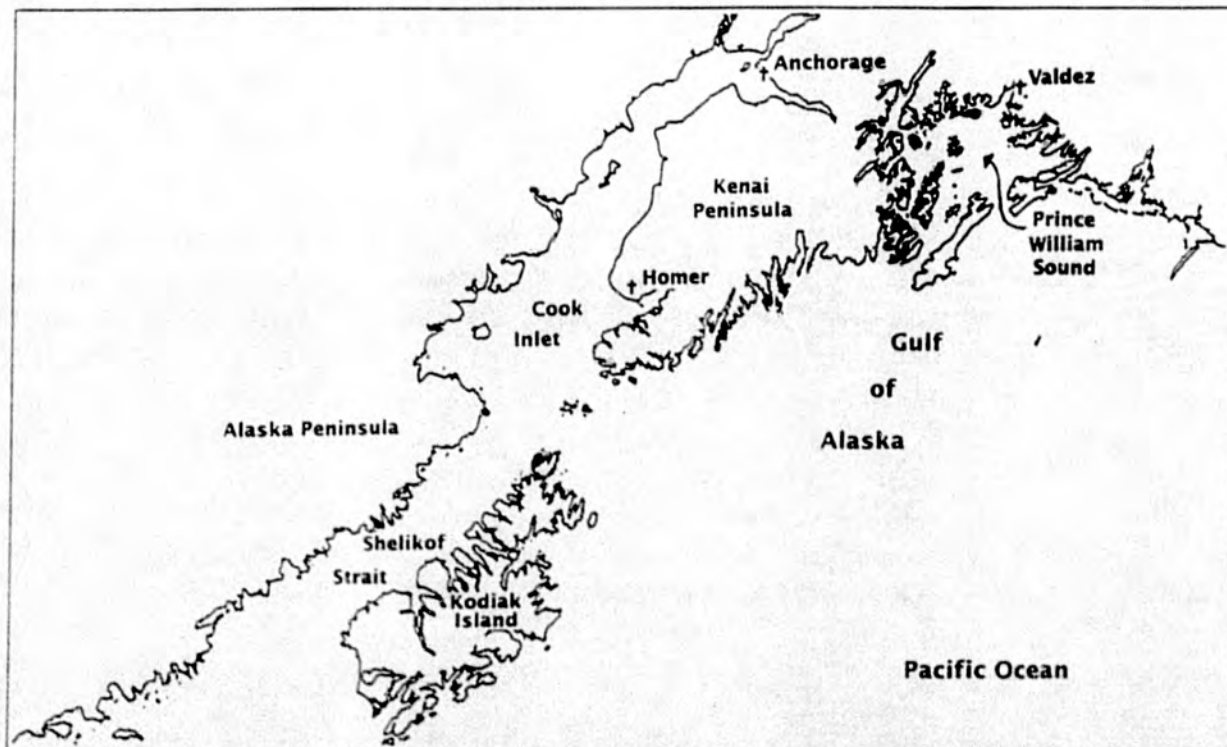
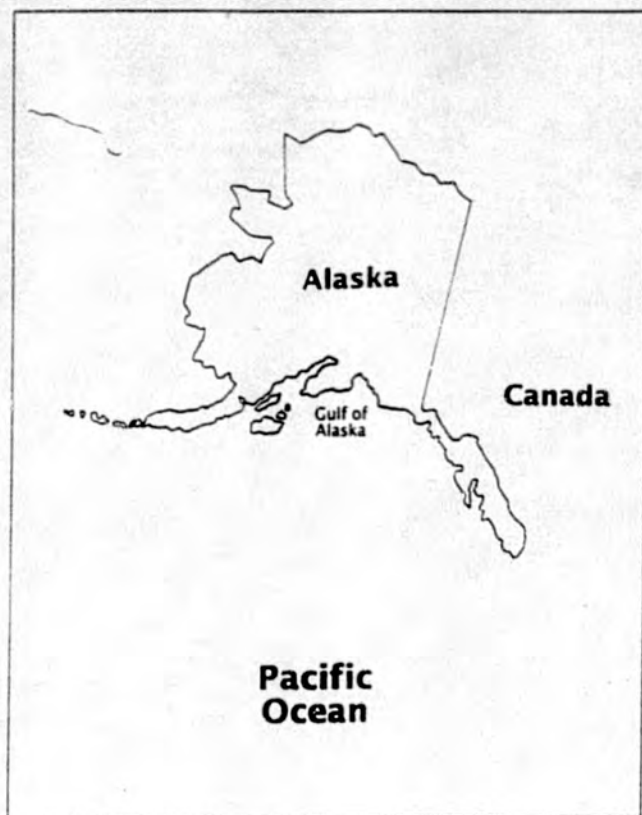


Figure 3
Prince William Sound Site Location Map

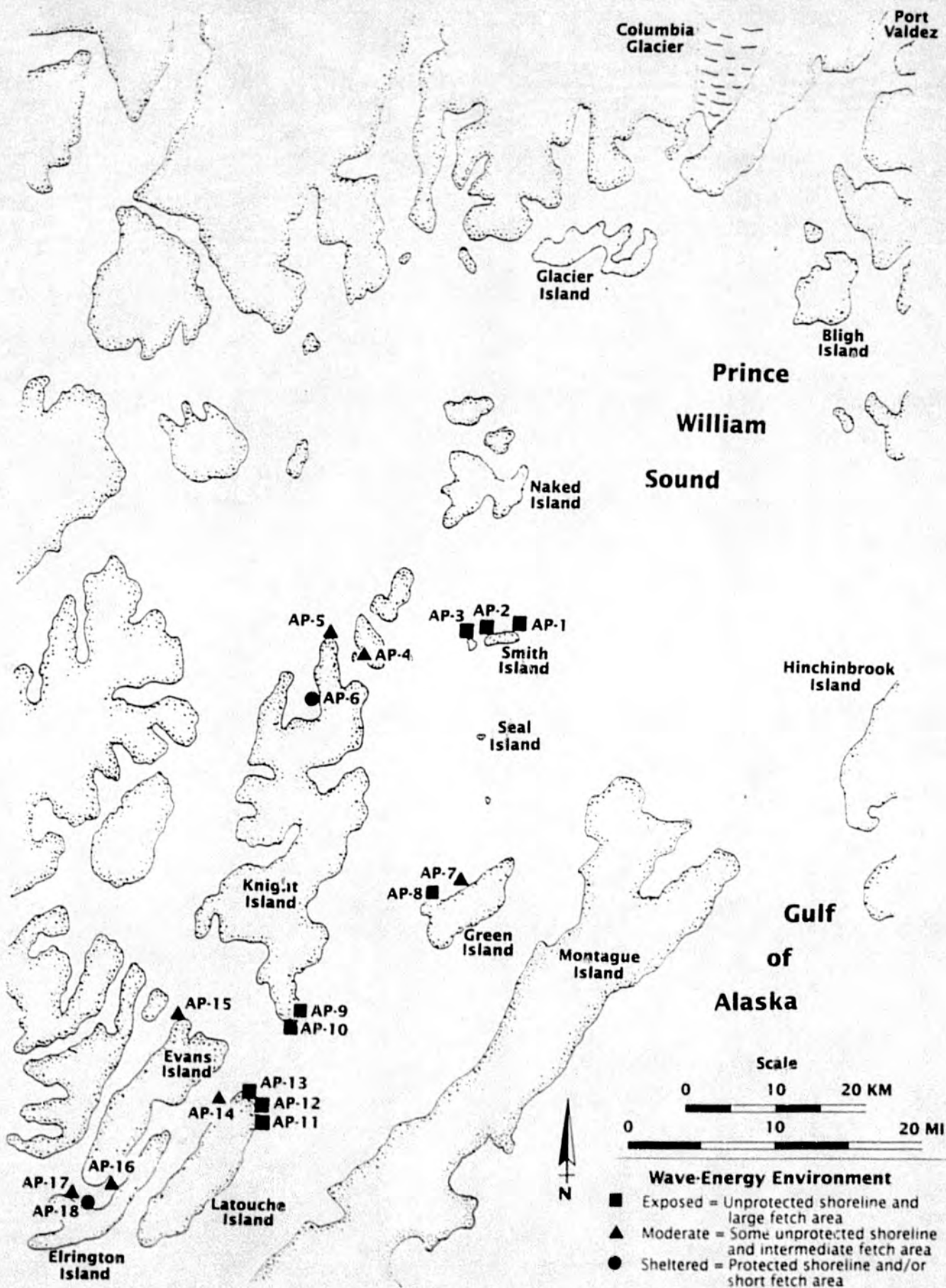
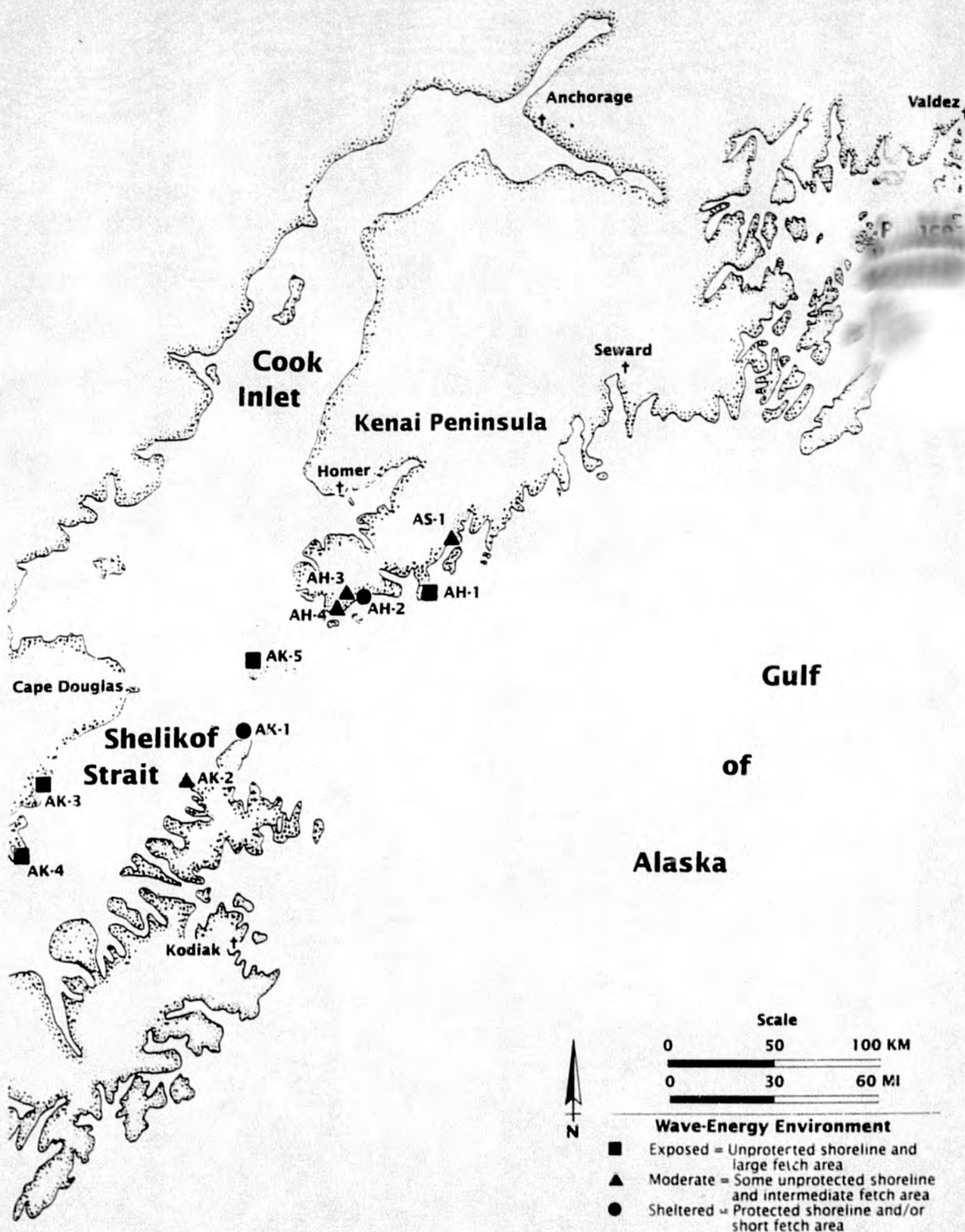


Figure 4
Kenai-Kodiak Region Site Location Map



OBJECTIVES AND METHODS

Program Objectives

The primary objectives of this study were to document and assess the fate and persistence of oil stranded on the coasts of Prince William Sound and the Kenai-Kodiak region after the spill. The program was designed to monitor the distribution of stranded oil on different shoreline types through time. The information was collected to help understand and assess the changing character of oil on the shorelines; it provided input for decisions and planning of appropriate shoreline treatment (Teal 1990). Study sites were chosen to represent the most heavily oiled conditions in the Sound and Kenai-Kodiak region. The field work for the program involved 28 study sites in 1989 and 26 sites in 1990. Surface oil cover and beach elevation measurements were made; sediment samples were collected for total extractable hydrocarbon (TEH) analysis; and test pits were dug to measure oil penetration. These studies were supplemented with detailed photographic and videotape transects of the study sites. This report includes data collected through September 1990.

The program focused on the collection of surface oil cover data, as this was considered to be a key indicator of changing oil conditions through time. Experience from previous studies had identified the difficulties associated with monitoring subsurface oil conditions and oil-in-sediment concentrations on coarse-sediment beaches. However, the study did include limited subsurface and oil concentration data collection on single transects at each site. The subsurface observations in the test pits of the systematic monitoring program, coupled with the TEH analysis, provided information on the character and changes in subsurface oil conditions. The study site observations are supplemented by data from other programs. During 1989, there were no systematic studies of subsurface oiling conditions during the regional surveys, but observations were made during the SSAT (spring 1990) program which enhance the monitoring program data. Although this report focuses on the information obtained as a result of the monitoring program, other observations and data are referenced and used to clarify a number of trends and significant points.

Study Sites

Twenty-eight primary sites were established: 18 in Prince William Sound and 10 in the Kenai-Kodiak region (Figures 3 and 4). Site locations are shown in Figures A-1 through A-9, on pages A-2 through A-10.

The Kenai-Kodiak region sites represent the most heavily oiled beaches in that region, but these were less oiled than the Sound sites at the beginning of the study. The Kenai-Kodiak sites that had the most oil cover were at Ushagat Island (site AK-5), Perevalnie Point (AK-1), Cape Kubugakli (AK-4), and Yalik Glacier Beach (AS-1) (Table 1, on the next page). The majority of the 18 sites in Prince William Sound also had initially continuous, wide-band oil coverage (Table 2, on the next page), and typified the range of substrate and beach dynamics observed in that region.

Tables 1 and 2, on the next page, show the characteristics of 28 study sites. Most sites in the Kenai-Kodiak region were less oiled than the Sound sites (Table 1). During the initial studies, most of the 18 sites in the Sound had continuous oil coverage wider than 6 m (Table 2).

Table 1
Kenai-Kodiak Region Site Locations and Characteristics

Site	Location	Original Oil Band Width	Wave-Energy Environment
AH-1	Gore Point	Medium	Exposed
AH-2	North Windy Bay	Medium	Sheltered
AH-3	Badger Cove	Medium	Moderate
AH-4	Chugach Bay	Medium	Moderate
AK-1	Perevalnie Point	Wide	Sheltered
AK-2	Black Cape	Medium	Moderate
AK-3	Cape Nukshak	Medium	Exposed
AK-4	Cape Kubugakli	Wide	Exposed
AK-5	Ushagat Island	Wide	Exposed
AS-1	Yalik Glacier Beach	Wide	Moderate

Note: Wide band equals > 6 m. Medium band equals 3 to 6 m.

Table 2
Prince William Sound Site Locations and Characteristics

Site	Location	Original Oil Band Width	Wave-Energy Environment
AP-1	Northeast Smith Island	Wide	Exposed
AP-2	Northwest Smith Island	Wide	Exposed
AP-3*	Northeast Little Smith Island	Wide	Exposed
AP-4*	Foul Pass, Ingot Island	Wide	Moderate
AP-5	Passage Point, Knight Island	Wide	Moderate
AP-6	East Herring Bay	Medium	Sheltered
AP-7	Central Green Island	Wide	Moderate
AP-8	West Green Island	Wide	Exposed
AP-9*	North Point Helen	Wide	Exposed
AP-10	South Point Helen	Wide	Exposed
AP-11	Northeast Latouche Island-South	Wide	Exposed
AP-12	Northeast Latouche Island-North	Wide	Exposed
AP-13	Sleepy Bay, Latouche Island	Wide	Exposed
AP-14	Northwest Latouche Island	Wide	Moderate
AP-15	North Evans Island	Wide	Moderate
AP-16	Southwest Elrington Island-East	Medium	Moderate
AP-17	Southwest Elrington Island-North	Medium	Moderate
AP-18	Southwest Elrington Island-Southwest	Medium	Sheltered

Note: Wide band equals > 6 m. Medium band equals 3 to 6 m.

* Not surveyed in 1990.

* AP-4 was originally classified as a sheltered, low-energy site. Based on field observations, particularly during the winter of 1989-90, the site was reclassified as a sheltered/moderately exposed location. Throughout this document, AP-4 appears as either sheltered or moderately exposed because it falls somewhere between these two categories.

A summary of the original oiling conditions and the wave-energy environments for the study sites (Table 3, on the next page) clearly shows that in Prince William Sound the program was biased toward sites with initially heavy oiling conditions.

Field Program

The first set of six sites in the Sound was staked and surveyed in May 1989. The program was expanded to 16 locations in late June to early July 1989 and then to 18 in August 1989. From September 1989 to September 1990, attempts were made on eight occasions to resurvey each location, with the following exceptions:

- AP-3 was not visited after November 1989 because no surface or subsurface oil remained.
- The stakes at AP-9 were removed accidentally by a cleanup crew in September 1989 and were not replaced because surveys of the site were duplicated by those of AP-10.
- Access difficulties by boat, due to winter nearshore wave conditions, and by helicopter prevented surveys of AP-15 from September 1989 to January 1990.

Nine locations in the Kenai-Kodiak region were established and surveyed in late July and early August 1989; a 10th site was added for the October 1989 survey. Attempts were made on eight occasions to resurvey each site from September 1989 to September 1990.

Field data collection was confined to periods when tidal water levels were less than +1.0 m above chart datum during daylight hours. This was a limiting factor between November 1989 and January 1990 when only one in three low tides coincided with daylight periods. A further necessary limitation was the adherence to safe operating practices and standards with respect to wind and wave conditions, resulting in the loss of one in four available working days. By contrast, transportation problems (vessel or aircraft mechanical failures) cost only 4.5 days out of the total 302 field days (Table 4, on the next page). The success of the operational phase of the winter program from September 1989 through March 1990 can be measured by the fact that no accidents or injuries were sustained during this winter program that involved a total of 650 manpower days in a remote, stormy environment. During the whole program, a total of 222 site surveys out of a possible 259 were completed between May 1989 and September 1990.

Table 3, on the next page, shows that no study sites were located in areas of narrow-band oiling (less than 3 m). Table 4 delineates field survey days. Of 302 days during the winter of 1989-90, weather accounted for 69.5 down days and mechanical problems for 4.5.

The field data set from the study sites upon which this report is based is summarized in Table 5, on page 13.

Table 3

Summary of Wave-Energy Environments and Initial Oiling Characteristics of the Study Sites

Prince William Sound		Oil Band Width		
Wave-Energy Environment		Narrow <3m	Medium 3-6m	Wide >6m
	Exposed	0	0	9
	Moderate	0	2	5
	Sheltered	0	2	0
Kenai-Kodiak Region		Narrow <3m	Medium 3-6m	Wide >6m
Wave-Energy Environment	Exposed	0	2	2
	Moderate	0	3	1
	Sheltered	0	1	1
Total Number of Sites		0	10	18

Table 4

Summary of Winter Field Activities/September 1989 to March 1990

	Total Field Survey Days	Weather Down Days	Mechanical Down Days	Total Days
Prince William Sound	107	22.5	1.0	130.5
Kenai-Kodiak Region	121	47.0	3.5	171.5
Total	228	69.5	4.5	302.0

Field Methods

Beach elevation and surface oil cover data were collected by coastal geologists on transects running approximately perpendicular to the shoreline. Each transect (profile) was controlled by backshore stakes that provided the line and starting point for the profile. Transects were generally spaced 20 m apart, although this distance was not used at all locations.

Table 5
Summary of Data Collected

From May 1989 to September 1990, 222 site visits were made. This report details data collected during those surveys.

1989	May	June/July	Aug.	Sept.	Oct.	Nov.	Dec.
Sites Visited	6	22	21	27	24	14	18
Elevation Profiles	81	173	91	122	66	29	45
Oil Cover Transects	83	242	200	232	207	111	174
Samples Collected	N/A	N/A	N/A	126	130	123	143
Subsurface Pits	4	27	25	94	65	86	108
Biological Transects	N/A	N/A	N/A	42	29	12	17
1990	Jan.	March	June	Sept.	Total for 1989 & 1990		
Sites Visited	20	23	28	19	222		
Elevation Profiles	35	35	269	93	1,039		
Oil Cover Transects	163	165	269	226	2,072		
Samples Collected	113	108	175	144	1,062		
Subsurface Pits	85	65	64	84	707		
Biological Transects	20	18	28	17	183		

N/A: Not applicable

Beach elevation change was generally determined at 2-meter intervals along the transect line. Surveys were performed using the Emery method, which employs two calibrated stakes and either the horizon or a bubble level to determine the horizontal plane (Emery 1961). The precision of this method, as used in this program, is ± 0.5 centimeter (cm)/reading if the rods are read to the nearest centimeter. The precision of elevations was checked by closing the surveyed transects; that is, elevations were surveyed back up the beach to the original starting point, and the difference from zero was calculated. For each survey, the average closing errors were equal to, or less than, the target of 0.5 cm/reading. The majority of closing errors were less than 10 cm for the entire transect. This error is acceptable because placing the stakes among boulders and cobbles along the beach may easily alter relative elevations by more than this amount.

Visual estimates of surface oil cover were made along the same cross-beach transects. Each oil cover observation represents the average value for the area 2.5 m on either side of the transect line and 2 m landward of the measurement point. This standard observation covers an area of 10 square meters (m^2) per reading.

Several test pits were dug in the beaches during each survey to determine the depth of oil penetration into the sediments (Photograph B-4, on page B-2). Pits were offset slightly from the transect lines to avoid artificially changing the oil cover observations. Many of the study beaches are dominated by boulders and cobbles, which made it impractical to dig pits or to estimate the downward extent of oiling.

Bulk surface and subsurface sediment samples were collected for gravimetric analysis of total extractable hydrocarbons (TEH). These grab samples usually were collected along two of the transects per site, at approximately equal intervals down the beach. Samples were placed in prelabeled 1-gallon (4-liter) bags and stored at ambient temperature until analyzed. This technique was designed to assess trends of oiling conditions and not to measure total amounts of oil present on a beach.

Photographs were taken to document field methods and the general appearance of the study sites. These photographs consisted mainly of overview shots of the area, surface sediments, oiling, and the test pits. A videotape record was made, generally on one of the transect lines, across the beach during each survey.

Biological transects were surveyed at the time of each site visit by coastal ecologists to document the distribution and abundance of major intertidal macro-species. These cross-shore transect surveys also involved photo documentation and data collection to monitor relative rates of recruitment. This data set is not included in this report, but a brief summary of the results, prepared by Dr. K. Critchlow, is given in Appendix G.

Data Reduction

The results of the elevation and oil cover surveys were transferred from field data sheets to spreadsheets from which a variety of calculated and summary values were generated. The data were then imported into graphics software to plot oil cover and elevation data versus distance along a transect for each survey date. This graphics package facilitated overlaying data from different field surveys.

In the data tables presented in this report, the term "total observed area" refers to the total area (in square meters) of beach observed during a survey. This value multiplied by the visual estimate of surface oil cover, expressed as a percent, provides the "equivalent oiled area" (in square meters). For example, a surface oil cover value of 80 percent over a total observed area of 10 m² at a point on a transect line gives an "equivalent oiled area" of 8 m². This follows the method developed by Owens et al. (1987).

The lengths of the transects that could be surveyed varied from one survey to the next because of tidal stage during the survey, weather conditions, and time available to conduct the survey. This variability makes direct comparison of unmodified data between surveys difficult.

The variability between the areas surveyed on the site visits may be handled by using a percentage oiled area, which is a term that expresses the sum of all equivalent oiled area values relative to the total surveyed area and is an aggregate of all oil cover observations.

Additional Surveys

The data from the monitoring program provide site-specific information through time. To evaluate the results in the context of the region as a whole, some data collected as part of systematic ground surveys have been included. These surveys were initiated and coordinated by Exxon and conducted by Woodward-Clyde coastal geologists and ecologists following a standardized methodology to ensure compatibility between survey teams and between surveys conducted at different times (Owens and Teal 1990a). Regional ground surveys were carried out in the summer of 1989 (Shoreline Cleanup Assessment Team - SCAT), February 1990 (FASST), April 1990 (SSAT), and August 1990 (ASAP).

One aspect of the 1990 shoreline treatment program involved the movement of oiled sediments from backbeach areas, where they remained unaffected by wave action, into the upper intertidal zone, where they could be treated by cleanup crews and abraded and cleaned by waves. Beach surveys were conducted at all sites where berm relocation was carried out before and after the sediment was moved. These surveys involved the measurement of elevations along cross-beach transects in the same manner as the surveys carried out at the long-term monitoring sites. Sediment relocation was used as a treatment technique at six of the long-term study sites.

As part of the winter monitoring program, time-lapse cameras were set up at five locations in Prince William Sound, including three of the long-term study sites (AP-1, AP-4, and AP-13). The photographs provide a time-series record of intertidal beach sediment and morphology changes and of breaker heights from November 1989 to April 1990.

RESULTS

Documented changes of shoreline conditions in Prince William Sound and the Kenai-Kodiak region are discussed from an analysis of the following data sets:

- Beach morphology;
- Surface oil cover;
- Subsurface oil observations; and
- Oil-in-sediment concentrations.

Surface oil cover is the most useful and accurate index of changing oil conditions (Humphrey et al. 1990). These data show that the quantity of oil on the shoreline has been reduced considerably, initially as a result of Exxon's cleanup operations, and later by natural cleaning through wave action and biophysical degradation. Experience from other oil spills in similar coastal environments suggests that almost all of the remaining oil will be fully degraded within the next few years.

A considerable database had been developed as a result of the monitoring program (Table 5) and it is beyond the scope of this report to comprehensively review all aspects of the information generated to date. The discussion contained in this report therefore focuses on key trends and observations. These trends are substantiated by other field observations and by the regional survey results.

Beach Morphology Changes

Changes in the surface configuration of beaches were monitored at the 28 study sites by repeated surveys of elevation along transect lines. The data provide a record of the net erosion and deposition of beach sediments in response to wave action. Additionally, beach morphology changes were recorded by time-lapse photography during the winter at two of the exposed, high wave-energy sites (AP-1 and AP-13) and one relatively sheltered site (AP-4) in the Sound.

Little change occurred during the relatively calm summer months because winds were generally light and, therefore, did not generate high-energy waves. Intense, low-pressure systems passing across the region during winter generated storm waves capable of redistributing and transporting even coarse-grained beach sediments such as boulders. In general, the largest beach changes occurred during winter on exposed sections of the coast, where the full force of breaking waves was spent on the shoreline. The winter erosion stage was followed by spring buildup as the eroded material was returned to the beach zone by constructive wave action.

During this program, more than 1,000 elevation transects were surveyed at the study sites. Representative examples from eight of the sites are given in Appendix C and discussed on the following pages in

order to highlight some of the observed changes. Beach profiles provide a record of long-term or net elevation changes that resulted from wave action between the survey dates. Time-lapse photography at the exposed AP-1 and AP-13 sites documents the almost continuous redistribution of sediments and the cycles of change that characterize these high wave-energy sites.

Prince William Sound Study Sites

Of the study sites that were regularly visited within the Sound, the greatest observed change occurred on northeast Smith Island (AP-1) (Photographs B-5 through B-10, on pages B-3 and B-4). This site is located on a straight section of shoreline with open exposure to waves from all northerly directions (Figure A-1, on page A-2). The beach is a mixture of granules, pebbles, cobbles, and boulders that rest as a relatively thin (1 m) veneer on a bedrock platform. Between the summer and mid-September of 1989, the western section of this exposed beach showed significant erosion in the vicinity of Transects 1 and 2 (Figure D-1, on page D-4). The eroded sediments had not been returned by June 1990 and were apparently transported to the east and deposited in the vicinity of Transects 9 and 10. This alongshore transport suggests strong wave action from a northwest direction. At the same time, the sediments in the central section of the beach (near Transect 8) were eroded and reworked down to the underlying bedrock platform (Figures C-1a and b, on page C-2). The profile data from this site show that:

- The western section was cut back 4 m laterally and eroded 1 m vertically (Photographs B-9 and B-10, on page B-4).
- The central section was eroded 0.5 m vertically during the winter, with the lowest elevations measured by the March 1990 survey; by June 1990, it was rebuilt to the same elevation as during June 1989 (Figure C-1a, on page C-2).
- The eastern intertidal zone was built up as much as 0.5 m (Figure C-1b, on page C-2).

The redistribution of these sediments had a profound effect on residual oil. Abrasion of oil-coated or oil-stained materials occurred as the sediments were moved around by breaking waves. At this site, the sediments were subject to high wave-energy conditions and to continuous reworking and redistribution, so most material within the zone of wave action was clean by the time of a site visit in November 1989. The abraded oil was washed from the beach by wave action and dispersed to be broken down by physical, chemical and biological processes.

Beach elevation changes recorded at the northeast Latouche Island site (AP-12) provide further examples of intertidal sediment reworking. This predominantly pebble-cobble beach is located in a broadly concave section

of coastline exposed to waves from north to southeast directions. Beach sediments at this site were reworked to depths on the order of 0.5 to 0.7 m by winter erosion, followed by spring-summer recovery.

Changes recorded at less exposed sites were less dramatic, but erosion of 0.2 to 0.3 m in the middle and upper intertidal zones was observed at most sites because of winter wave action (e.g., AP-16, Transect 3; Figure C-3, on page C-3). Oil was removed at sheltered sites because even small waves were able to abrade and erode the oil, which was on the beach surface because fine-gravel sediments inhibited penetration.

With storms passing through the region, beach erosion was accompanied by deposition of the intertidal sediments in the adjacent nearshore subtidal zone. Storm events were interspersed with periods of beach recovery when sediments were returned to the beach from the subtidal zone as bars or ridges that migrated up the beach under constructive wave action. This sequence of storm-wave erosion and ridge recovery was observed on several occasions in the time-lapse photography from the Sleepy Bay study site (AP-13) (Photographs F-1 to F-5, on pages F-11 to F-12).

Not all exposed sites underwent major changes. The high-energy, cobble-boulder beach at South Point Helen (AP-10) showed virtually no elevation changes in the middle and lower intertidal zone through the winter (Figure C-2, on page C-3). This lack of change was a result of the well-packed, coarse surface sediment layer that protected the underlying beach sediments against wave energy in that section of the beach. The sediments that formed the armor layer were moved by wave action, so surface oil was abraded. The armor, however, prevented subsurface sediment reworking and thus limited the amount of oil that could be removed by winter storms.

Beach transect data from study sites where sediment relocation was carried out provide valuable information on the effects of that program. For example, at AP-13, in August 1990, a 0.5 meter-high swash ridge migrated up the beach within three days after relocation of sediments from the berm area to the intertidal zone, as waves worked to restore an equilibrium profile (Figure C-8, on page C-6).

Kenai-Kodiak Region Study Sites

Beaches at the exposed Kenai-Kodiak region study sites (Gore Point, AH-1; Black Cape, AK-2; Cape Kubugakli, AK-4; and Ushagat Island, AK-5) underwent major erosion over the winter months, with surveyed beach elevation changes in excess of 1 m at all of these locations. Clearly, any oil that had been deposited within those zones of beach erosion was reworked, washed, abraded, dispersed and degraded. Profiles from AK-2 (Figure C-5b, on page C-5) show:

- A progressive lowering of the beach surface by about 1 m between September 1989 and December 1989 with removal of the high-water berm and flattening of the beach profile
- The return of some of the sediment to the beach between December 1989 and June 1990. This beach appears to undergo cycles of erosion and recovery on an annual basis. Oil had been buried by a 2-5 cm layer of clean sediments at the time of the first site visit in July 1989, and the clean layer and buried oil were removed by subsequent wave action by October 1989.

Transect data from the Ushagat Island (AK-5) site, in the Barren Islands group, reflect some of the highest shoreline wave-energy conditions in the region. This wide and low angle, pebble-cobble beach is exposed to ocean swells and storm waves from southwest to northwest directions (Figure A-7, on page A-8). Storms prior to the December 1989 survey transported sediments up the beach, above the normal intertidal zone, to form new storm berms up to 2 m thick (Figure C-7, on page C-6). By March 1990, much of this berm zone on the northern sections of the beach, including all of the areas where oil had been deposited, had eroded to levels below those of the first survey. In contrast, on the southern section of the study site, oil on the berm remained buried by as much as 1 m of clean sediment. In September 1990, this clean overburden was moved aside, and the layer of buried oiled sediments was relocated across the beach to the high-water level, to be reworked by winter wave action.

The Cape Nukshak (AK-3) site is located in Hallo Bay and consists of a boulder beach mixed with sand, gravel, and cobble material. The partially sheltered location is exposed to moderate wave-energy from Shelikof Strait (Figure A-9, on page A-10). The beach transects surveyed at this site showed relatively little change through the summer and fall of 1989. Higher-energy winter waves in this location eroded the middle and lower intertidal zone by as much as 1 m between mid-October 1989 and the beginning of January 1990 (Figure C-6, on page C-5). Wave conditions were not sufficiently energetic to alter the higher sections of the beach, i.e., the storm berm located above the + 5 m level. By June 1990, the beach had rebuilt to the same elevation recorded in the September 1989 survey. A similar pattern of little change before October 1989, followed by a period of erosion, is shown in the second example from a moderate wave-energy environment (Badger Cove, AH-3). This site is located in a cove on the Kenai Peninsula and consists of a cobble and gravel beach exposed to Gulf of Alaska waves from south to southeast directions (Figure A-7, on page A-8). Initially, the oil was buried by a thin layer of clean sediment but this oil was later removed when the beach was lowered about 0.4 m across the middle and lower intertidal zones and up to 1 m in the upper intertidal zone between July 1989 and early December 1989 (Figure C-4, on page C-4). However, at this site the beach had not rebuilt up to the levels of the previous summer by the June 1990 survey.

In contrast to the exposed and moderately exposed wave-energy sites, the North Windy Bay (AH-2) and Perevalnie Point (AK-1) data indicate that these sheltered beaches underwent little change in either beach configuration or sediment distribution during winter. Oil residues were removed at these sites, indicating that physical processes, such as wave action, do operate, albeit at a reduced level.

Surface Oil Cover Changes

Site surveys from May 1989 to September 1990 resulted in 156 site maps for the Sound and 77 for the Kenai-Kodiak region. Surface oil cover data for each survey are summarized as the total (percent) oil cover for each site (Table 6, on the next page). The oil cover value is obtained by dividing the equivalent oiled area by the total observed area, as described on page 14. The trend of decreasing surface oil cover through time is evident from the data (Figure 5, on page 22). Berm relocation and tilling activities exposed subsurface oil and spread oiled sediments from the backshore over the upper intertidal zone at sites AP-1, AP-2, AP-10, AP-12, AP-13C/W, AK-1, and AK-5, and caused an increase in the surface oil cover at AP-12, AP-13C, AP-13W, AK-1 and AK-5 at the time of the September 1990 survey. The objective of relocation was to move oil that was out of reach of 1989-90 winter wave action, and therefore was expected to have a long residence time, into the zone of wave abrasion and cleaning.

The highest average oil cover value (79 percent) was recorded in the Sound at site AP-1 in late June 1989, but by January 1990 the highest site value had decreased to 22 percent (at AP-2). The first zero oil cover value in the Sound was recorded at the exposed high-energy site on Little Smith Island (AP-3) in October 1989, and seven of the 18 Prince William Sound sites had surface cover values of less than 5 percent at the time of the January 1990 survey. By September 1990, 20 of 27 sites had a cover of 2 percent or less, and eight had no visible oil.

The average oil cover value of the six sites in the Sound that were surveyed in May 1989 was 46 percent. The average cover for all of the sites surveyed in January 1990 was 12 percent and had decreased to 2.5 percent in June 1990. One site, AP-2, falls outside of the general trends, with changes occurring at a slower rate than comparable sites. This beach is on the same exposed, high-energy coast as sites AP-1 and AP-3, both of which dropped to low values by mid-winter. The reasons for this variability between nearby sites are discussed on page 38.

The monitoring sites have produced a data set for the Sound that primarily describes changes for heavily oiled shorelines because 14 of the 18 sites originally had an oil band greater than 6 m wide (Table 3). The data may not be directly extrapolated to all of the Prince William Sound coastline because this category accounted for only approximately

Surface oil cover data for surveys from May 1989 to September 1990 are summarized in Table 6, on the next page. The percent of surface oil cover, relative to observation area, at study sites shows a marked decrease through time, as shown by Figure 5, on page 22. Each line is the average of all sites within the three wave-energy categories.

Table 6
Percent of Surface Oil Cover

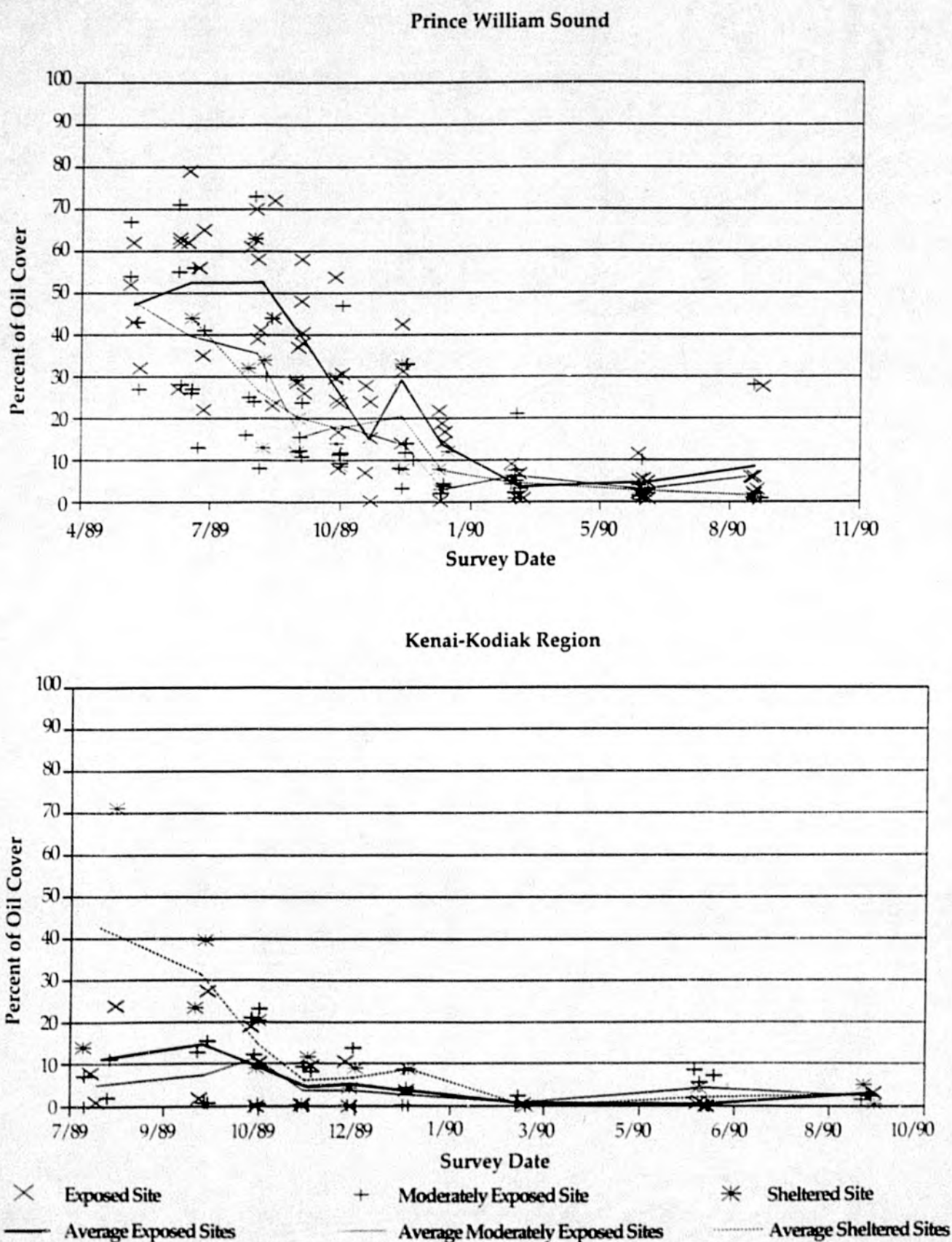
SITE	5/89	6-7/89	8/89	9/89	10/89	11/89	12/89	1/90	3/90	6/90	9/90
AP-1	-	79		28	29		14	-		2	2
AP-2	-	62		38	54		42	22		11	6
AP-3	32	22		26	-		-	-		-	-
AP-4	-	-		29	30		33	12		2	2
AP-5	43	41		-	11		8	-		1	-
AP-6	-	-		12	8		-	8		4	1
AP-7	-	13		11	11		-	4		2	-
AP-8	-	56		40	24		-	14		5	6
AP-9	-	65		-	-		-	-		-	-
AP-10	-	35		37	24		-	19		5	3
AP-11	43	63		48	17		-	-		1	-
AP-12	62	62		58	31		31	17		5	27
AP-13E	54	55		-	-		14	-		3	1
AP-13C	67	71		-	47		33	-		10	28
AP-13W	52	27		-	8		-	0		1	6
AP-14	27	28		24	-		12	4		3	0
AP-15	-	56		-	-		-	-		3	1
AP-16	-	27		12	9		10	2		1	1
AP-17	-	26		15	12		3	2		0	-
AP-18	-	44		20	14		8	3		2	2
AH-1	-	1		2	0		0	-		0	-
AH-2	-	14		23	9		4	-		0	0
AH-3	-	0		1	0		0	0		0	-
AH-4	-	7		13	21		0	0		0	-
AK-1	-	-		40	20		9	9		4	5
AK-2	-	2		1	0		0	0		0	-
AK-3	-	-		15	23		-	4		5	3
AK-4	-	-		27	10		-	4		1	-
AK-5	-	8		-	19		10	-		1	3
AS-1	-	-		-	12		14	9		8	1

Note: Site AP-13 was subdivided into three sections (East, Central and West) but is considered as a "single" site in most instances.

- Site not visited.

* Site visited but no measurement taken.

Figure 5
Surface Oil Cover Versus Time



20 percent of the original length of oiled shorelines in the Sound. Furthermore, band width alone does not take into account variations of the initial severity of oiling. Other factors related to the degree of initial oiling include oil thickness, depth of penetration, patchiness, and viscosity. However, the data set represents those areas that were most heavily oiled and where oiling was expected to persist longest. Therefore, the data set presents a bias toward worse-case conditions.

Field surveys in the summer of 1989 support the generalization that oil was scattered and generally light in the Kenai-Kodiak region. The oil bands at AK-4 and AK-5 were both wide initially, but on these large beaches the initial average oil cover values were artificially low because of the extensive proportion of unoiled surface material surveyed in the middle and lower intertidal zones. If one looks only at the oiled areas of these two beaches rather than the total observed areas, the original oil cover values were reduced from 100 to 7 percent by January 1990 at AK-4 and to 0.7 percent by March 1990 at AK-5, so the average values in Table 6 do reflect a real change (Table D-2, on page D-3).

Oil Cover Maps

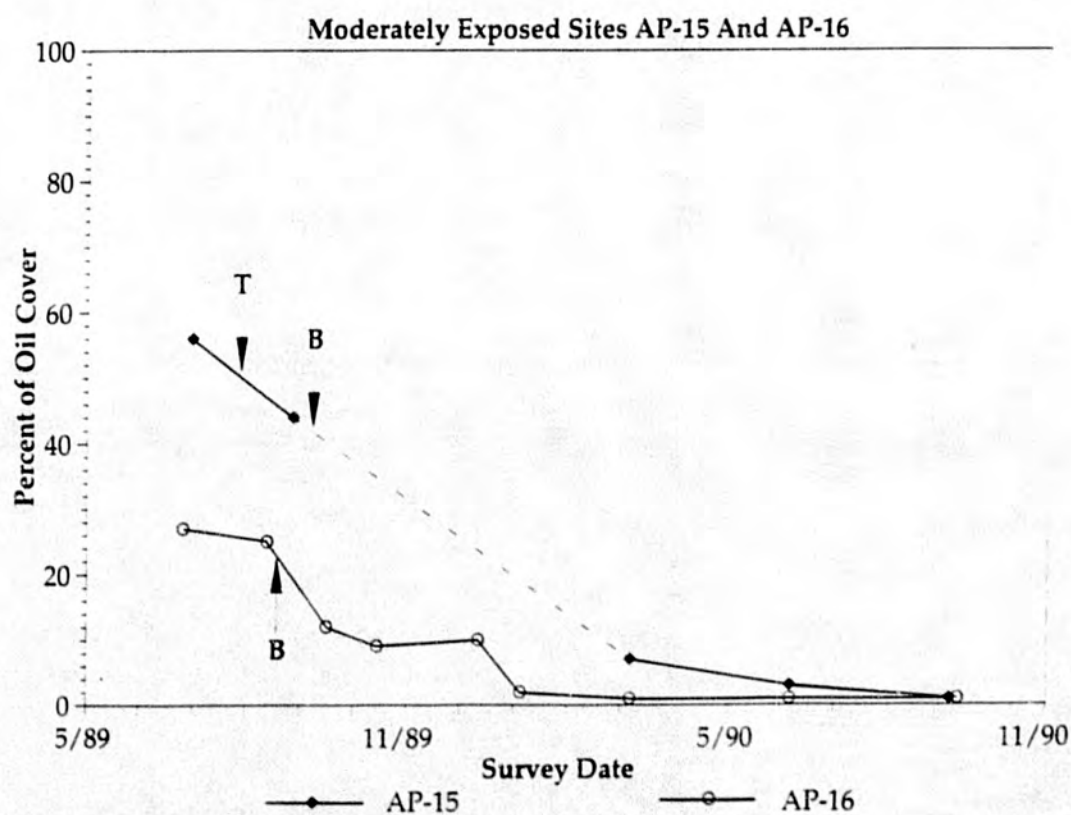
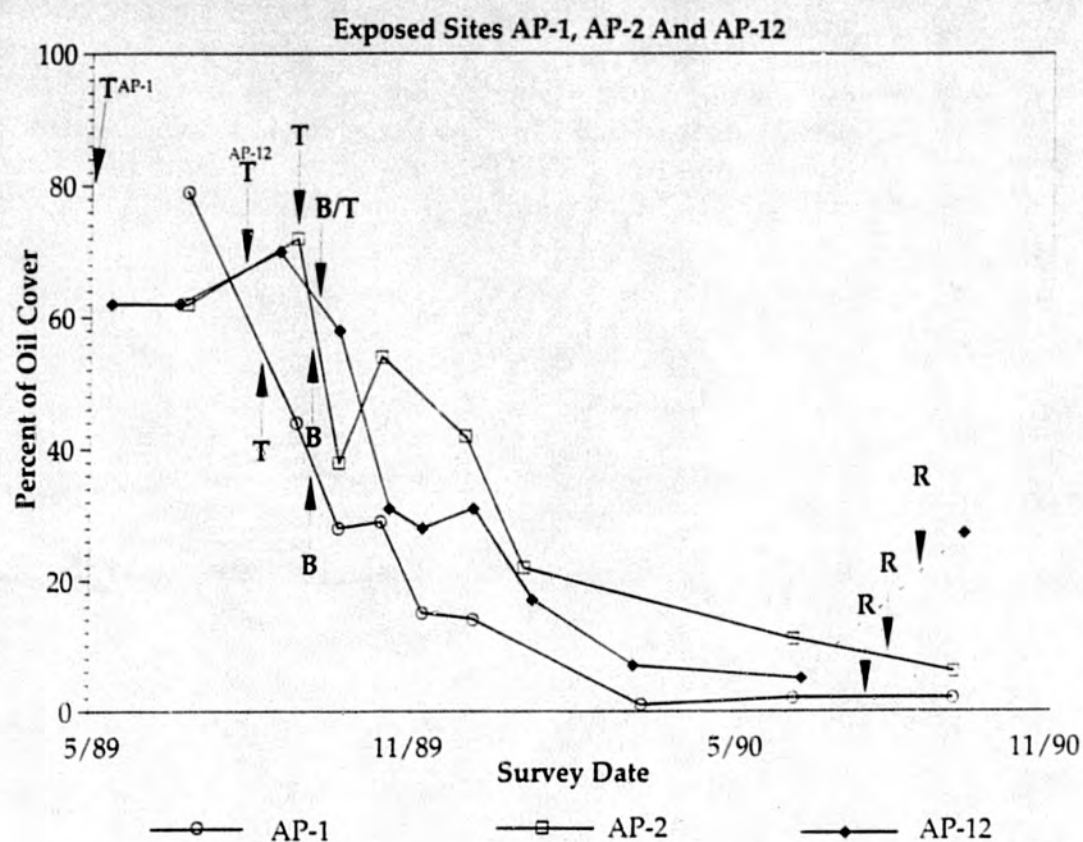
The changes in the distribution of surface oil cover through time are illustrated in a selected set of maps (Appendix D). Criteria for the selection are:

- Prince William Sound
 - Two data sets from each of the exposed, moderately exposed, and sheltered sites in the Sound; these two sets would represent the greatest and least surface cover at the time of the March 1990 (end of winter) survey.
- Kenai-Kodiak Region
 - Three sites from the Kenai-Kodiak region that represent the range of wave-energy environments and that initially had an extensive surface oil cover.
- General
 - Individual maps from the time series at each site that represent a significant change or that illustrate a trend.

Changes in percent of surface oil cover, relative to observation area, are obtained by comparing only the area of beach repeatedly documented by all surveys. Figure 6, on the next two pages, shows that Prince William Sound sites and Kenai-Kodiak sites had major reductions of surface oiling following summer 1989.

Data for each of the sites and the treatment activities that took place during 1989 are summarized in Table 7a, on page 26, and Table 7b, on page 27. Representative maps for each site illustrate the major changes that took place in the distribution of oil on the beaches (Appendix D). The changes are summarized in a set of graphs (Figure 6, on the next two pages) based on an analysis of oil cover transect data.

Figure 6
Transect Surface Oil Cover Changes Over Time

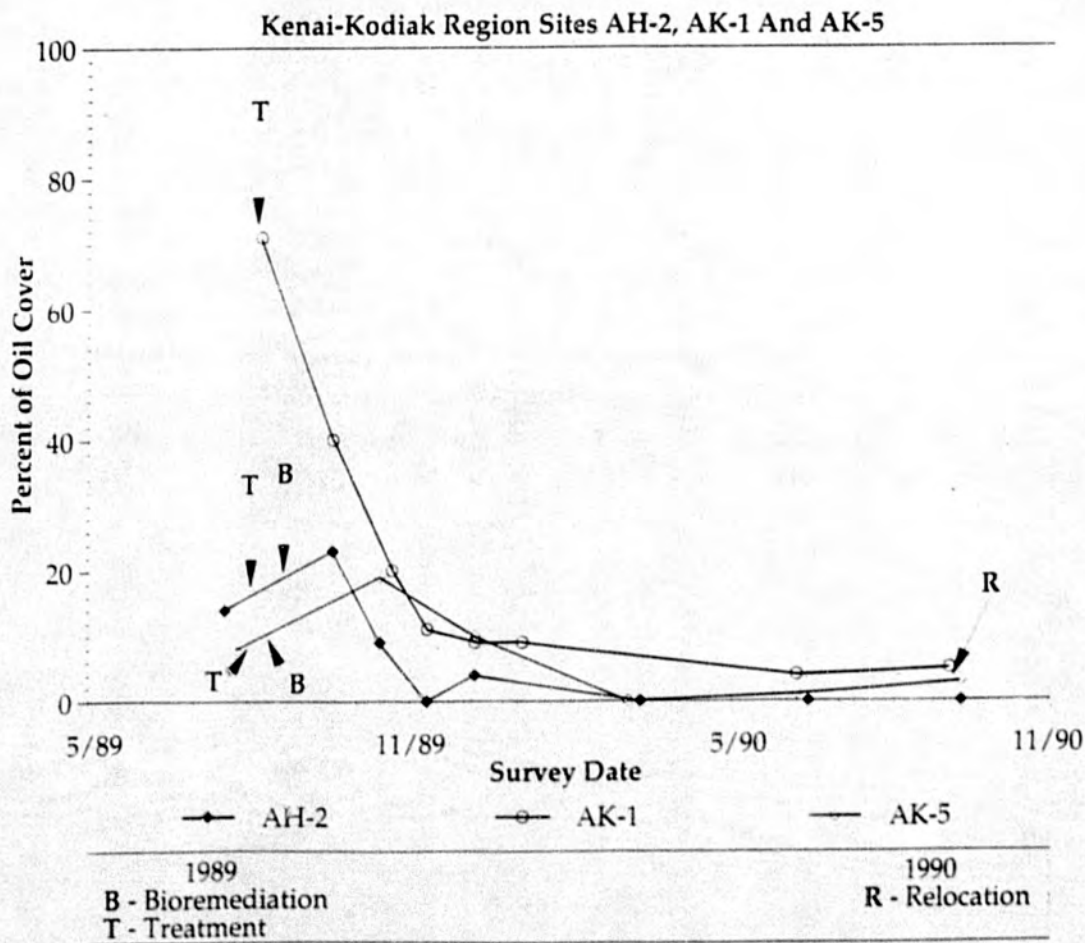
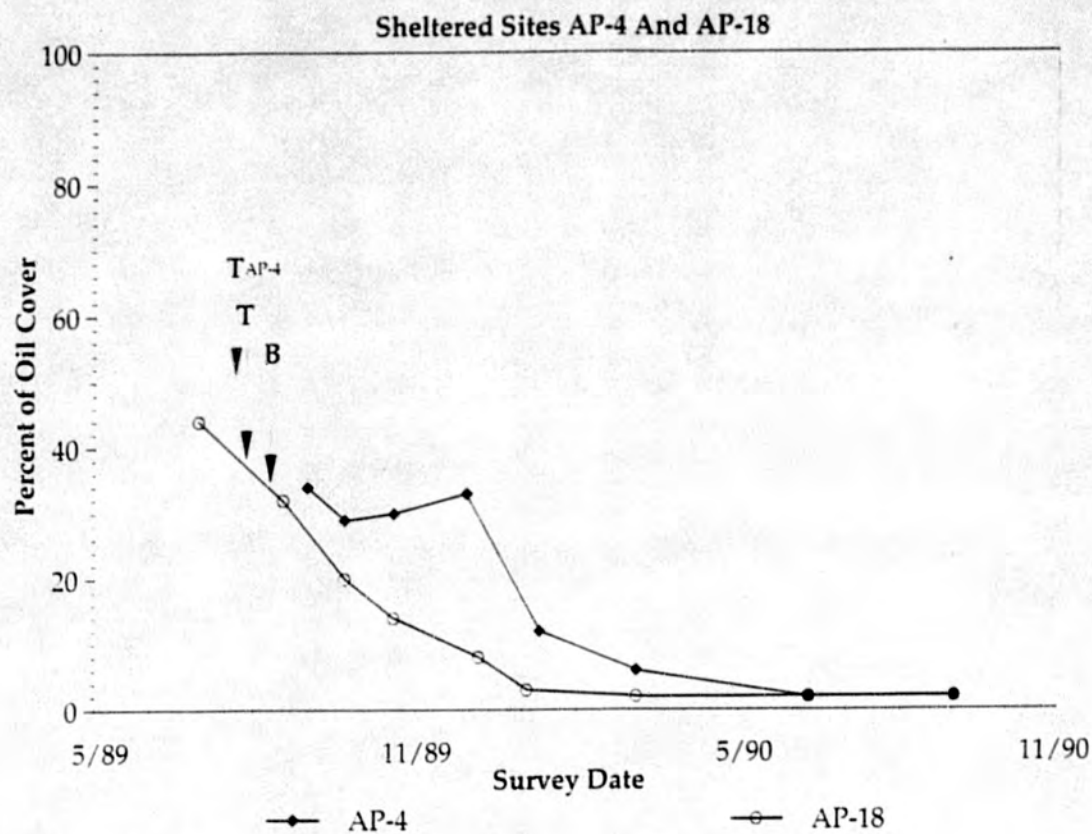


1989
B - Bioremediation
T - Treatment

- - - Interpolated Data

1990
R - Relocation

Figure 6
Transect Surface Oil Cover Changes Over Time / Continued



Ten sites were selected to illustrate changes in the distribution of surface oil cover through time. Site characteristics are shown in Table 7a and treatment histories in Table 7b, on page 27.

Table 7a
Selected Study Sites/General Characteristics

Site	Wave-Energy Environment	Initial Oiling Category	Initial Oiled Area (m ²)	Summer 1990 Oiled Area (m ²)
AP-1 Northeast Smith Island	Exposed	Wide	1,565	40*
AP-2 Northwest Smith Island	Exposed	Wide	1,073	97*
AP-12 Northeast Latouche Island-North	Exposed	Wide	2,037	204*
AP-15 North Evans Island	Moderate	Wide	605	6*
AP-16 Southwest Elrington Island-East	Moderate	Medium	411	11*
AP-4 Foul Pass, Ingot Island	Moderate	Wide	507	27*
AP-18 Southwest Elrington Island-Southwest	Sheltered	Medium	690	28*
AH-2 North Windy Bay	Sheltered	Medium	614	1*
AK-1 Perevalnie Point	Sheltered	Wide	366	37*
AK-5 Ushagat Island	Exposed	Wide	451	27*

*- September 1990 survey data

— June 1990 survey data (prior to sediment relocation)

The maps shown in Appendix D are a product of transect data. An important feature of the monitoring program was that each site had multiple transect lines across the beach. Owens and Teal (1990b) have shown that single transects have limited value because there is considerable alongshore variability in the distribution of oil on most beaches.

The data in Table 6 were obtained by dividing the actual observed oil cover by the total observed area at each site. The total observed area varied from survey to survey because of daily and monthly differences in the height of the low tides at the time of each survey, and because of snow on the upper beach in winter (particularly during the January and March 1990 surveys). In contrast, the data in Figure 6 reflect only that part of the beach that was common to all surveys.

Specific Results

Prince William Sound Exposed Environments

The examples of exposed sites (AP-1 and AP-12) were initially heavily oiled both in terms of oil coverage and of oil concentration, with the northeast Smith Island site (AP-1) being among the most oiled in the Sound. Changes in beach morphology at these sites are discussed on page 17.

Selected study sites were grouped by similarities, as shown by the line divisions in this table.

Table 7b
Selected Study Sites/1989 Treatment Histories

Exposed Sites in Prince William Sound

- | | |
|-------|---|
| AP-1 | 1. Cold water deluge and wash in late April/early May 1989
2. Deluge and warm water wash completed on Aug. 13, 1989
3. Bioremediation on Sept. 8 and 12, 1989 |
| AP-2 | 1. Deluge and warm water wash in late August and early September 1989
2. Bioremediation on Sept. 8, 11 and 12, 1989 |
| AP-12 | 1. Deluge and warm water wash in August and September 1989
2. Bioremediation on Sept. 14, 1989 |

Moderately Exposed Sites in Prince William Sound

- | | |
|-------|--|
| AP-15 | 1. Warm water flush by MAXI barge on July 20-23, 1989
2. Manual removal of oiled debris and hand wiping on July 20-23, 1989
3. Bioremediation on Sept. 9, 1989 |
| AP-16 | 1. Bioremediation on Aug. 16, 1989 |

Sheltered to Moderately Exposed Sites in Prince William Sound

- | | |
|-------|--|
| AP-4 | 1. Warm water flush by MAXI barge on July 24-30, 1989 |
| AP-18 | 1. Manual removal of oiled debris (Summer 1989)
2. Bioremediation on Aug. 6, 1989 |

Kenai-Kodiak Region Sites

- | | |
|------|---|
| AH-2 | 1. Manual pickup in August 1989
2. Bioremediation on Aug. 15, 1989 |
| AK-1 | 1. Manual pickup of surface oil and hot water washing (Summer 1989) |
| AK-5 | 1. Manual pickup July 25 to Aug. 12, 1989
2. Bioremediation on Aug. 12, 1989 |

The timing of some of the observed changes at these locations reflects the treatment activity schedule. For example, AP-1 initially had a 100 percent oil cover in the intertidal zone and was treated by cold-water washing in April 1989 before the first survey, and by warm water washing in August 1989 before the second survey. The oil cover map (Figure D-1, on page D-4) reflects these activities: Oil cover on this beach dropped from an average value of 79 percent before the August treatment to 44 percent in the post-treatment survey due to a combination of treatment and late August storms (Table 6 and Figure 6). Fluctuations of oil cover at AP-1 during the early summer of 1989 could have been the result of "free" oil from within the porous beach being re-stranded on the beach surface. Following these summer 1989 reductions, surface oiling at AP-1 was further reduced by wave action (Photographs B-5 through B-10, on pages

B-3 and B-4). Two major storms, in mid-October 1989 and early November 1989, coincided with high spring tides to produce waves capable of reworking sediments on the upper beach so that by the time of a site visit on Nov. 20, 1989 the intertidal zone was essentially free of surface and subsurface oil.

In contrast to AP-1, a similarly oiled site (AP-12) was not treated until August 1989 when the central and western segments were washed. The eastern segment was washed in September, and then the entire beach was bioremediated on Sept. 14, 1989. The surface maps and oil cover data from this site show virtually no significant reductions through Sept. 19, but the average dropped over a four-week period from 58 percent on Sept. 19 to 31 percent by Oct. 20, 1989 (Figure D-3, on page D-6; and Table 6). This sharp reduction, which is mirrored in the detailed transect analysis (Figure 6), was a result of the combined effects of the treatment activities and of two major winter storms that passed through the region during Oct. 4-8 and 15-21, 1989. Both storms had peak winds over 85 km per hour (hr), and the second had sustained average winds greater than 50 km/hr out of the easterly directions for four days, at a time of high spring tides (Appendix E). A time-lapse camera was installed on the adjacent AP-13 site, and between Nov. 11, 1989 and April 12, 1990, breaking wave heights of greater than 0.5 m were observed during daylight hours on a total of 20 days (Appendix F). By June 1990, only a very narrow strip of oil-coated or oil-stained sediments was left on the surface at the highest parts of the beach at AP-12, which is reworked only by high waves during spring tides.

At both AP-1 and AP-12, winter wave action was not able to reach oil deposited during high spring tides above the normal high water level. During the 1990 summer cleanup program, these residual oiled sediments in the storm berms were mechanically relocated across the beach and spread over the upper intertidal zone, where loose oil was picked up manually; the oil-coated sediments were left to be reworked and redistributed by wave action. At AP-12, this activity occurred immediately before the September 1990 site visit, and that survey accurately reflects an increase in the surface oil cover from 5 percent in June before the treatment to 27 percent in September.

Prince William Sound Moderately Exposed Sites

The first example in this category is provided by a small pocket beach, part of a tombolo, located on the northwest coast of Evans Island (AP-15) (Figure A-5, on page A-6). The predominantly granular beach is partially exposed to waves generated in Knight Island Passage. Treatment of the beach at this site by washing before the August 1989 survey reduced the total surface oil cover by about 20 percent, but the beach still had patches of greater than 50 percent cover throughout the intertidal zone (Figure D-4, on page D-7). No surveys were conducted during the winter due to access difficulties, but by March 1990, the winter wave action, probably

augmented by late-summer 1989 bioremediation, had reduced the oil cover to some patches on the northern end of the study site. By June 1990, these patches had been reduced even further; and by September 1990, the surface oil cover was 1 percent, indicating that spring-summer wave action played an important role in natural surface cleaning on this moderately exposed beach.

The second example in this category is provided by a 180-meter-long, low-angle beach at the south end of Elrington Passage (AP-16) (Figure A-6, on page A-7). The beach is composed of granules, pebbles, and cobbles and is protected from all directions except to the northeast. The site was not extensively oiled to begin with, and was treated only with bioremediation on Aug. 16, 1989. Data from the two pretreatment surveys (June 27 and Aug. 10, 1989) indicate that little oil removal had occurred over that six-week period. By contrast, the Sept. 18, 1989 survey indicated that the oil cover was reduced by half (Table 6). The detailed transect analysis shows a similar change (Figure 6). This was a period of very little storm activity so the change is likely attributable to a combination of abrasion and washing by small breaking waves and the bioremediation treatment. Winter wave action continued the cleaning process so that by March 1990 only scattered patches of oil-stained sediments remained, generally in the upper intertidal zone (Figure D-5, on page D-8).

Prince William Sound Sheltered Sites

The first example in the sheltered category is provided by a beach located between Ingot and Disk Islands (Figure A-2, on page A-3). The Ingot Island study site (AP-4) is on a cusped spit where beach sediments consist of poorly sorted granules, pebbles, and cobbles. The site was treated by washing before the first survey (Aug. 22, 1989), but a wide band of oil remained along the upper beach (Figure D-2, on page D-5). This cover was largely unmodified through December 1989 (Figure 6) despite breaker heights of more than 1 m on Nov. 22. The change between the December and January surveys is dramatic. During that four-week period, two major storms (Dec. 11-12 and 27-31) generated dominant winds out of the southeast, with peak wind speeds greater than 110 km/hr. Spring high tides occurred at the same time as these storms. These winds and resultant waves coincided with the narrow fetch window at this site and reworked, washed, and abraded the oiled sediments. Time-lapse photography of the southern half of this site recorded 25-centimeter waves or larger on six days during December (2-3; 10-12; 27) that were coincident with easterly or southeasterly winds (Appendix E). Site AP-4 also appears to have been exposed to, and influenced by, strong northerly winds. Reduction of surface oil cover occurred on the northern side of the spit in response to these storms, as indicated by field observations during December 1989/January 1990. Some further cleaning took place over the remaining winter months, but well over three-quarters of the change that was recorded between August 1989 and March 1990 occurred between the December and January surveys.

A second sample of a sheltered site is provided by the south Elrington Island site (AP-18). This beach is located on the east side of a cove, along a narrow stretch of shore separating the cove from north Twin Bay (Figure A-6, on page A-7). This protected beach is formed of cobbles, sand, and pebbles. Oil cover reduction at site AP-18 occurred earlier than at AP-4, with most reduction taking place between the June and August 1989 surveys (Figure 6). The site was bioremediated on Aug. 6, but it is unlikely that all the reductions recorded by Aug. 9 reflect this treatment because insufficient time had elapsed for the biological process to be effective. The changes between the August and September 1989 surveys were not large, but a second period of major change took place between Sept. 17 and Oct. 16, 1989. The transect analysis from that period shows that the oil cover was halved (Figure D-6, on page D-9). The two major storms that occurred on Oct. 4-8 and 15-21, 1989 may have caused this change. The latter storm was a particularly important event because it coincided with one of the highest spring tides of the year (Table F-1, on page F-2).

Kenai-Kodiak Region Trends

Three sites in the Kenai-Kodiak region illustrate very different situations from the Sound sites. The exposed Ushagat Island site (AK-5) had an initial wide band of oil on the beach. The low total oil cover for this site indicates that most of the beach was not oiled. A better measure of the amount of change at this location is to compare the values for the actual oiled area, rather than use a fraction or percent value for the entire beach. The surface oil cover doubled between late July and October 1989 because wave action distributed the original stranded oil over higher parts of the beach. By December 1989, winter wave action reduced the oiled area to about the original cover. The beach had little surface oil cover remaining by June 1990, but the beach transect data (Appendix C) indicated that some burial had occurred. A survey of the site in June 1990 showed that the reduction of the oil cover over the winter months was a result of erosion of beach material in the northern half of the study site and burial of oiled sediments in the southern half. This site is one of the few where large-scale burial of oiled sediments was found by the regional ground surveys. Cross-beach trenches cut by a power shovel showed that the distribution of the buried layer in June 1990 corresponds to the surface oil cover map for December 1989. Relocation work in early September 1990, to expose the oil that had been buried on the berm, was followed by a site survey that showed the surface oil cover increased to 3 percent from 1 percent in June of that year.

The north Windy Bay site (AH-2) is a sheltered, long, and low-angle site located in a pocket cove (Figure A-7, on page A-8). Sediments on this beach consist of gravel, sand, and mud. This sheltered location had a 3- to 6-meter-wide band of oil stranded on the upper beach at the time of the

first survey in July 1989. Manual pickup had taken place before the first survey. Wave action was effective at this site in further cleaning the beach, and no surface oil remained by the March 1990 survey. The beach profile had not changed significantly through time, so it is unlikely oil was buried.

A wide band of oil stranded at Perevalnie Point (AK-1) was removed by manual pickup and washing, leaving only oil-coated and oil-stained sediment by the September 1989 survey. The site is a low-angle, cobble and gravel beach located in a small cove between steep, rocky outcrops. Bedrock underlies the thin beach cover at this site. Low wave energy characterizes this shoreline because the site is protected from the Gulf of Alaska by the Perevalnie Islands (Figure A-8, on page A-9). Some natural cleaning occurred between the September and November 1989 surveys, but no subsequent changes were noted, although the amount of remaining oil was small.

Sites With Berm Sediment Relocation Treatment in 1990

Evaluation of the SSAT survey results indicated that oil remained on some beach berms in the spring of 1990 above the normal high-water level (in the supratidal zone) and had not been reached by winter wave action. A treatment technique for this type of situation was developed that involved relocating that material downslope into the upper intertidal zone to accelerate the natural cleaning processes. Once relocated, any free oil was picked up manually or by using sorbent materials, and the remaining oil was then to be abraded, reworked, and dispersed by waves through the summer and, particularly, the 1990-91 winter months. Bioremediation was carried out after relocation to enhance degradation of the residual oil by native bacteria. The SSAT survey also defined a few areas of subsurface oil that had not been reworked by winter wave action. For these latter situations, a tilling approach was recommended, in which the subsurface oil was brought to the surface and exposed to wave action and biodegradation.

Comparison of surface oil cover observations made before and after the treatment activities at the sites indicates a considerable reduction in the occurrence of residual oil in the supratidal zone. Of the 26 sites with observations before and after berm relocation, the number with a wide or moderate oil cover in the upper intertidal zone was reduced from 19 to eight and, significantly, the number of sites with a wide or moderate cover in the supratidal zone was reduced from eight to one (Table 8, on the next page). An expected consequence of the relocation and tilling was a temporary increase in surface oil cover in the upper intertidal zone at some sites (for example, at AP-12, AP-13C/W, AK-1, and AK-5, as shown in Table 6). Summer wave action was observed to have reworked and redistributed sediments on exposed beaches; however, the greatest changes were expected to have occurred over the 1990-91 winter months.

After berm relocation, only nine of 26 sites still had a wide or moderate cover in August/September 1990.

Table 8
Changes in Oil Cover by Tidal Zone and
Oil Category/26 Berm Sediment Relocation Sites

		Supratidal Zone		Upper Intertidal Zone	
		Pre-Treatment	Post-Treatment	Pre-Treatment	Post-Treatment
Oil Cover Category	Wide, Heavy	5	0	14	2
	Moderate	3	1	5	6
	Narrow	2	2	4	6
	Very Light	1	5	2	9
	No Oil	15	18	1	3

Discussion - Rates of Change

All of the field observations, maps, and transect analyses show that significant reductions in surface oil cover occurred during the 1-1/2 years after the spill. By September 1990, eight of the 26 sites had no surface oil, and a further 16 sites had a 5 percent or less cover. The oil that remained after the winter was located, for the most part, on the highest sections of the beach, above the limit of normal wave action. This zone is reworked only during periods of spring high tides or by major storm waves, and the residual oiled sediments were moved across the beach where they could be reworked by waves. Surface relocation treatment resulted in increased surface oil cover values at five sites because of sediment relocation before the September 1990 surveys.

The results of the 1989 summer treatment program are evident at most locations. The effects of treatment are probably underestimated by the surface oil cover data because this approach does not take into account reductions in the oil thickness and oil-in-sediment concentrations. The role of winter wave action is clearly demonstrated as the slower rates of change from January 1990 onward coincide with the relatively calmer wind and wave conditions experienced over that period at most sites, in marked contrast to the more energetic period from September to the end of December 1989. This change in rates of removal also occurs, in part, because the oil that was more easily removed had been mechanically removed by wave action by the end of December, so less oil was available to be removed.

Rates of natural cleaning by weathering would be expected to vary considerably from site to site and from year to year, depending primarily on the coincidence of winds and waves with the fetch window for a given site. The rate of change also varies within a single beach system. The latter is evident from inspection of the maps in Appendix D.

The variability from one location to another is often due to subtle changes in the local coastal environment. Three adjacent sites on northern Smith Island are compared to illustrate this point. The three sites are similar in character and have the same exposure in terms of fetch distances, but each is

affected differently by storm winds because of their different beach orientations (Figure A-1, on page A-2). The comparison addresses the reduction of the area of surface oil cover and relates changes to both treatment history and occurrence of onshore storm winds (Figure 7, on the next page). For ease of comparison, rates of change as shown in Figure 7 are normalized to the initial equivalent oiled area, which is taken as 100 percent. The following discussion is based on the raw data shown in Table 6, on page 21.

Northeast Smith Island (AP-1)

This beach is exposed to storms out of the northwest through northeast directions. The sequence of changes in the surface oil cover is:

- Original oil cover (April 1989) was 100 percent in the intertidal zone, which is equal to approximately 80 percent of the total surveyed area.
- Most of the surface changes occurred prior to Sept. 16, 1989, following two periods of extensive treatment (Table 7b), by which time oil remained on only 28 percent of the surveyed area because of treatment and summer wave action.
- Virtually no change occurred between Sept. 16 and Oct. 15, 1989, during which there were no storm winds out of the north or northeast.
- Further reduction of surface oil cover to 15 percent occurred by Nov. 10, 1989 following storm winds out of the north on the two previous days and during Oct. 16-21; the October storm may have been the more important because it coincided with very high spring tides.
- Reduction to 1 percent occurred by March 1990, with 10 storm events out of the northwest and north during that interval.

The AP-1 site was affected by three major storms and four additional storms with onshore winds between mid-October 1989 and early June 1990 (Photographs B-5 through B-10, on pages B-3 and B-4). The effects of the two periods of extensive treatment activity, followed by strong storm-wave activity during the early winter, are considered to be the primary causes of the initial lowering of the quantity of oil on the beach.

Northwest Smith Island (AP-2)

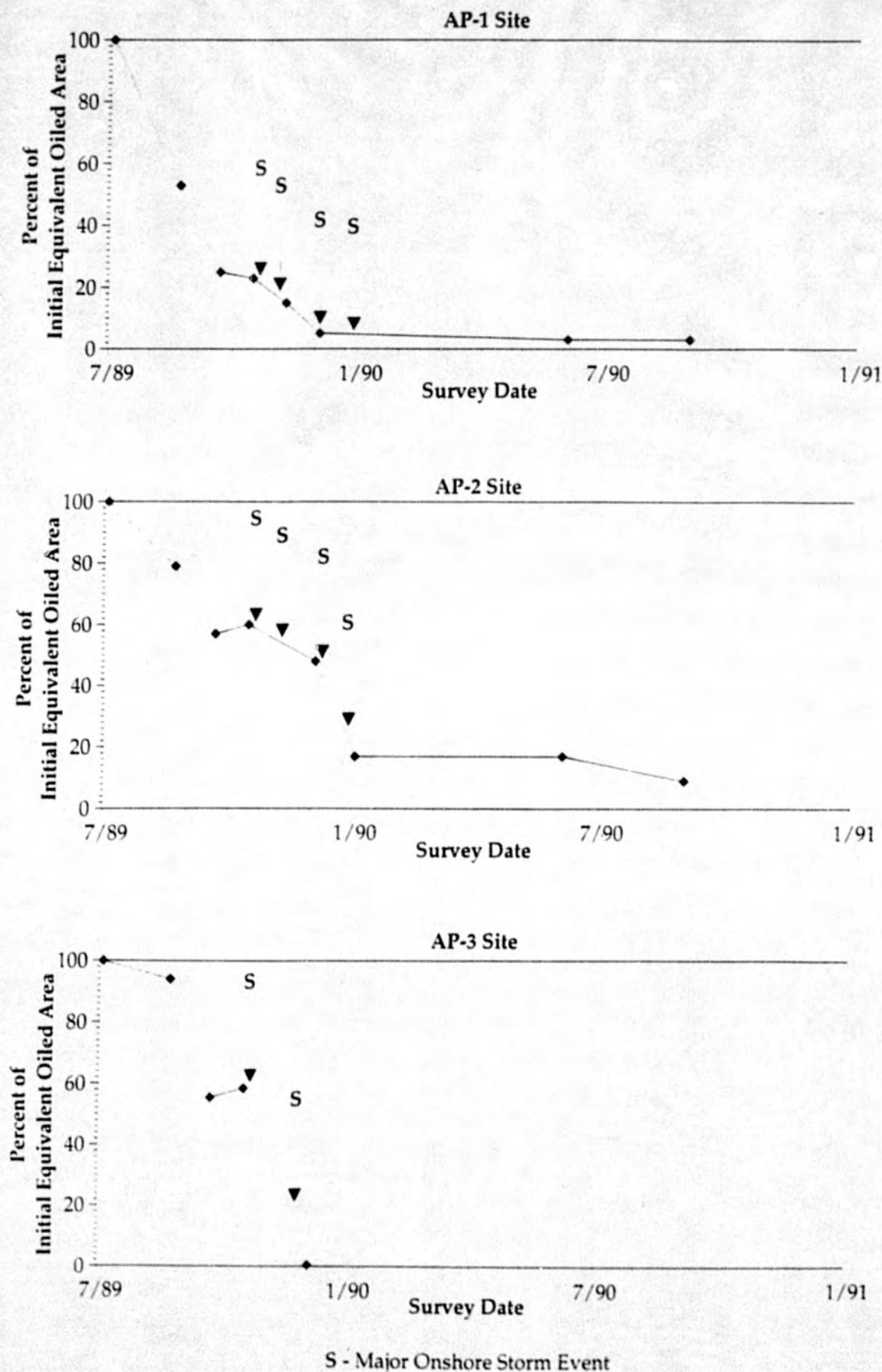
Although oriented east-west, this beach is partially sheltered to the northeast and is exposed to storms only out of the northwest to north window. The pattern of change at this location is as follows:

- The beach had a complete (100 percent) oil cover in April 1989.

Figure 7, on the next page, shows the percentage of surface oil remaining at Smith Island sites AP-1, AP-2, and AP-3. Major storm events affecting these sites produced large waves that reworked, abraded, and washed surface sediments.

Figure 7

Smith Island Surface Oil Changes Over Time/Initial Oil Taken as 100 Percent



- Treatment activities reduced the area of surface oil cover to 38 percent by the time of the Sept. 20, 1989 survey.
- No reduction took place between Sept. 20 and Oct. 14, 1989 (Table D-2, on page D-3), during which period there were no storm winds out of the north or northwest.
- Surface oil cover was reduced from 54 percent on Oct. 14, 1989 to 42 percent by the Dec. 4, 1989 survey, probably as a result of storms out of the north in mid-October and early November 1989.
- A major reduction to 22 percent happened between Dec. 4, 1989 and Jan. 2, 1990, associated with strong onshore storm winds out of the northwest during Dec. 30-31.
- No further reduction of the oiled area occurred between Jan. 2 and June 5, 1990 (Table D-2, on page D-3), during which period six secondary storms with strong onshore winds affected this site.

The surface oil cover on AP-2 was not removed as much as the surface oil cover at the two other sites in this comparison, although the site was subject to three major storms and several additional onshore storms. The major onshore storms mechanically worked the beach sediments and reduced the surface oil cover from 54 to 22 percent. Most of the post-treatment change at this site, however, can be related to the December 1989 storm events. The subsequent secondary storms caused no further change, probably because the wave washing and abrasion were less effective at removing weathered oil. The slower reduction in the surface oil cover is attributed to the limited level of treatment in comparison to AP-1 during 1989, and to shoreline orientation, which sheltered the beach from direct wave action out of the east and northeast during the early winter storms.

Northeast Little Smith Island (AP-3)

The final beach in this comparison faces the northeast and is exposed to storms out of the north through to the east. Changes at this location were:

- The treatment program and summer wave action reduced surface oil cover to 55 percent of the original (May 1989) oiled area (Table D-2, on page D-3).
- Little change took place between Aug. 28 and Sept. 21, 1989, during which there were no storm winds out of the north or northeast.
- All remaining oil was removed between Sept. 21 and Nov. 11, 1989 as a result of two major onshore storms; one out of the north-northeast on Oct. 15-21, coincident with spring tides, and a second storm out of the north on Nov. 6-10.

The AP-3 site was cleaned by a combination of the treatment activities followed by two major onshore storms that occurred relatively early in winter 1989-90. Shoreline orientation and the exposure of this beach to east and northeast storms are considered to be the primary causes for the rapid cleaning at this site.

Discussion - Cleaning Processes

The difference between the rates of natural cleaning at the three exposed and adjacent Sound sites (AP-1, AP-2, and AP-3), and at the two sheltered Kenai-Kodiak sites (AH-2 and AK-1) illustrates that exposed, moderate and sheltered wave-energy categorizations oversimplify the complexity of the processes that operate in the coastal system. The three Smith Island sites are all north-facing, but rates of change during the winter were induced by storm waves out of specific directions. Similarly, adjacent sites AP-11 and AP-12 on northeast Latouche Island were also cleaned at different rates during the winter because of different shoreline orientations. The east-facing AP-11 beach was not treated during 1989 but was almost oil free by mid-November 1989 after a succession of five onshore storms during early winter. In the case of the sheltered, low to moderate wave-energy AP-4 site in the Sound, this beach was largely cleaned by two major storm events during which wind speeds in excess of 110 km/hr were aligned with the narrow fetch window for that location. One of these storms was the strongest event of the winter in the Sound. Natural cleaning rates were clearly sensitive to shoreline orientation and exposure. It is evident that the mechanical work produced by wave action on a beach can play a critical role in removal, transport, and weathering of oiled sediments. In addition, fine sediments are more easily entrained than coarse material and can be an effective abrasive tool, even on moderately exposed or sheltered beaches.

This cleaning action is also very dependent on the character of the stranded oil. Wave abrasion and cleaning are more effective on the lighter hydrocarbon compounds than on weathered oil; therefore, natural cleaning rates would be expected to be greatest when waves directly rework beach sediments at an early stage relative to initial oil stranding. In this respect, the observed cleaning rates of the spill could easily have differed because of the variability of storm wave intensity, coincidence of storms and spring tides, wind and wave directions, and timing of oil stranding relative to the winter storm season.

The natural cleaning of oiled shorelines results from a range of physical, chemical and biological processes that contribute to different degrees and that operate on different time scales. Immediately following a spill, the most important processes are spreading and evaporation. Once oil has become stranded, wave abrasion, washing, and flushing are the primary removal processes. During the summer of 1989, the Exxon flood-and-flush treatment program, as well as natural wave washing and

flushing, resulted in the removal of most of the free or mobile oil from the shorelines of Prince William Sound. Further removal occurred over the winter months by storm-wave abrasion and washing so that by mid-winter, the oil that remained was primarily as coats or stains.

Natural biodegradation of oil residues is a significant process after wave action or washing has removed the thick oil deposits. This weathering process was enhanced, following large-scale field trials in 1989, by the addition of fertilizers to areas where oil-coated or oil-stained material was present. This bioremediation technique is thought to have increased rates of natural bacterial degradation of oil by a factor of five (Prince, Clark, and Lindstrom 1990). During the 1990 treatment operations, at sites designated for bioremediation, the fertilizers were added on a regular basis to provide a continuing source of nutrients for the oil-degrading bacteria.

The set of long-term monitoring sites does not include a location that is representative of sheltered bedrock outcrops. Regular visits to sections of coast in Northwest Bay and Upper Passage that contained this shoreline type indicated that by January 1990 there had been a significant reduction of the oil cover on bedrock outcrops and boulders. In many sections the intertidal oil had been removed completely, even in very sheltered areas where wave action would not have been a factor in natural cleaning. A laboratory study by Exxon Production Research Company, using oiled material collected from northeast Smith Island and from Meares Point on Perry Island, showed that the residual oil was associated with large amounts of very fine sediment particles (silts and clays) (Bragg et al. 1990). Fine sediments are common in the waters of Prince William Sound because "glacial flour" is carried by streams that originate in the ice fields of the hinterland. Simulated tidal action resulted in a flocculation-like process that formed clay-oil aggregates, which detached from the oil on the pebbles or cobbles (Jahns et al. 1991).

The process by which the particles interact with the residual oil and seawater to form the clay-oil aggregates may have been responsible for oil removal on many sheltered sections of coast in the Sound. The washing and removal of most of the oil by the summer treatment activities left a relatively thin oil coat or stain on bedrock and boulder surfaces and made possible this secondary natural cleaning process. This process, combined with photodegradation and dispersion, also significantly increases the oil-water interface and thereby makes the residual oil readily available for biodegradation. Although the process is relatively minor when compared to the volume of oil removed from the shorelines by the washing and flushing activities, the removal of the thin residue contributed to the natural cleaning of the shorelines.

Observations during the spring 1990 SSAT survey identified some residual oil at a few sites on the highest parts of the beach that had not been reworked and cleaned by winter wave action. This oil had been deposited in the supratidal zone either by spring tides or by storm waves and was beyond the reach of most wave activity. In order to expedite the natural cleaning of these oiled sediments, a program of sediment relocation was

developed which involved movement of the material from the supratidal beach into the the upper intertidal zone, where it could be abraded and washed by waves.

The combination of treatment activities and natural cleaning is documented by the observations and data from the study sites and by site visits elsewhere in Prince William Sound and the Kenai-Kodiak region. The picture that emerged in the spring of 1990 was one of basically clean shorelines with residues where wave action and Exxon's activities had not been able to reach the oil. Although the cleaning processes involved different mechanisms and operated on different time scales, the net effect was that most of the oil was removed from the shorelines within a year after the spill.

Subsurface Oil Conditions

By their very nature, subsurface oiling conditions are difficult to characterize and to monitor over time. Observations were made at each study site along a transect to describe the presence and type of any oil below the beach surface. This information is supplemented by observations from pits dug as part of other programs. Many of these observations were made during the joint regional surveys. The trends that have emerged, and that are summarized in the next few paragraphs, therefore represent a compilation of various data sources with examples selected to illustrate the major findings. The overall conclusion is that subsurface oil was not a common occurrence in 1990. Where subsurface oil had been identified during 1989 surveys, little remained by the end of 1990.

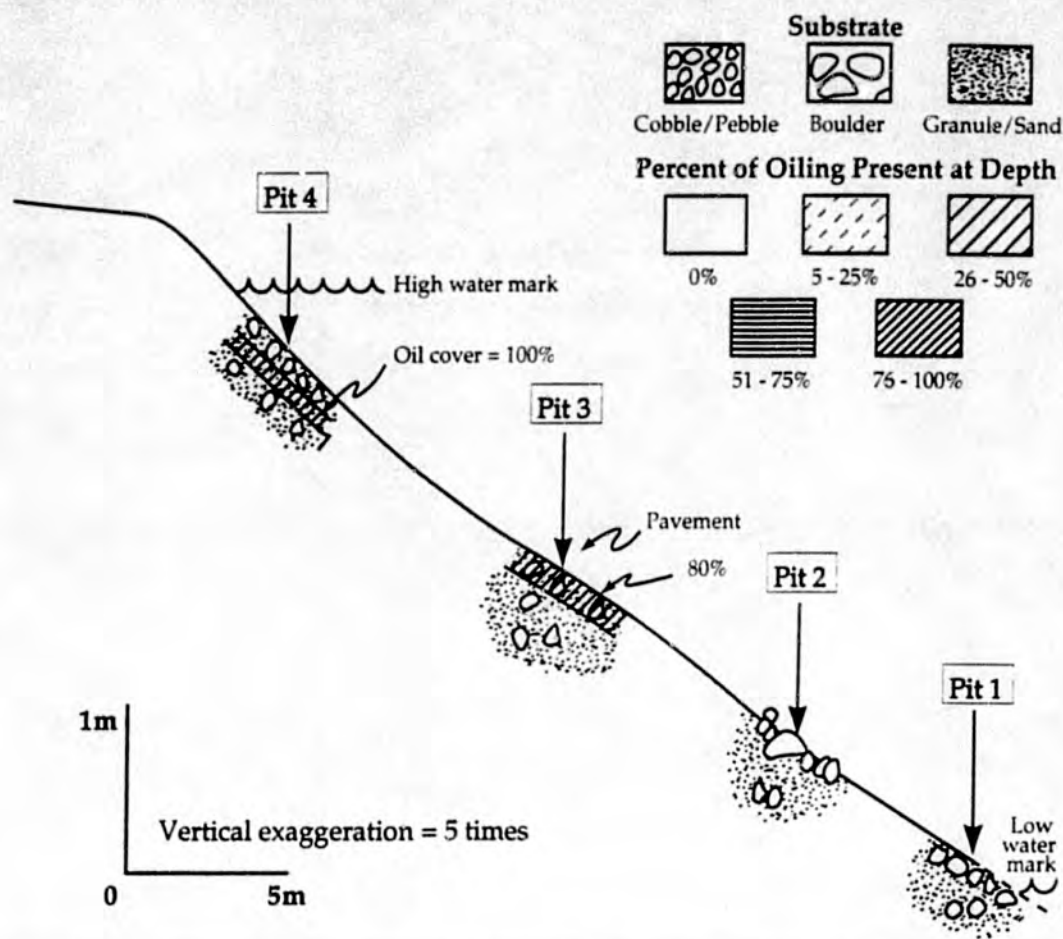
Over the winter and spring of 1990, more than 5,000 pits were dug (including SSAT and FASST surveys) to ascertain the character and penetration of subsurface oil. Oil that was observed in subsurface sediments had either penetrated down through pore spaces between the particles after stranding, or had been reworked or buried as a result of wave action redistributing beach sediments.

The many subsurface observations indicate that deep (50-100 cm) oil penetration was limited to a relatively few well-sorted, coarse-sediment beaches. Oil penetrated up to 1 m on a few coarse-grained beaches where no fine-grained sediments filled the large pore spaces between particles. This beach type is not common in the study area. Elsewhere, oil penetration was generally limited to the upper 10 cm of the beaches because fine-grained sediments have a low permeability to oil (Little et al. 1981; Michel et al. 1990). In addition, low permeability sediments retain more water on an ebbing tide, thereby further inhibiting penetration.

Most of the subsurface oiling information was collected during the spring 1990 SSAT survey. During that survey, oil was found at depths greater than 30 cm in 127 pits, along approximately 16 km out of the more than 2,000 km of shoreline that were surveyed. Two-thirds of this affected shoreline was accounted for in three stretches characterized by coarse-

Figure 8
Subsurface Pit Sketch/West Herring Bay

A cross-section of the beach at West Herring Bay shows that the presence of fine-grained sediments limited oil penetration. The oil found in Pit 4 on Jan. 18, 1990 was an asphaltic layer that had been covered by clean sediments.



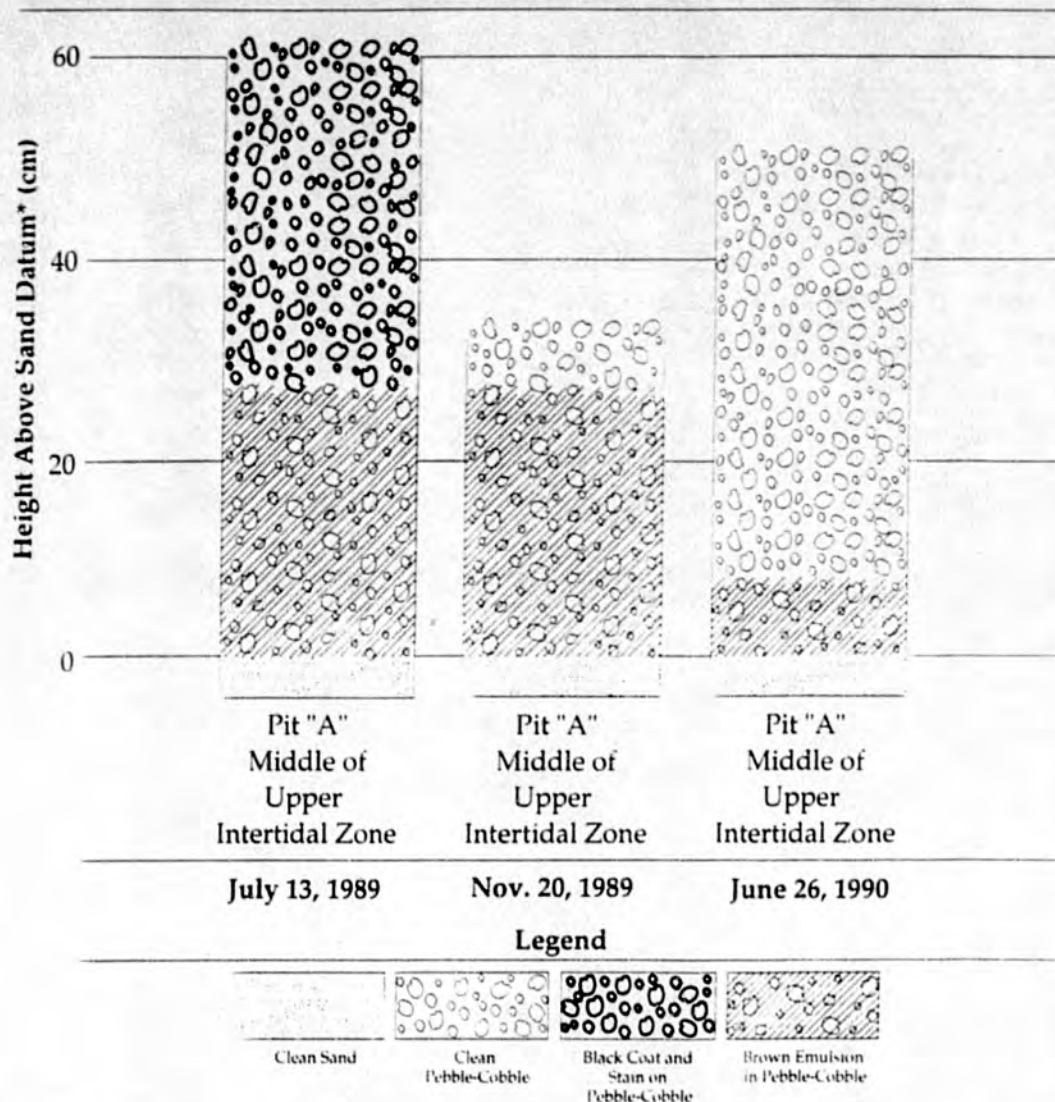
sediment beaches. Shorefast booms were deployed in April 1990 adjacent to these three beaches, which are long-term monitoring study sites (northeast Smith Island, AP-1; south Point Helen, AP-10; and Sleepy Bay, AP-13), to contain any oil that might be released as warmer summer temperatures reduced the oil viscosity. During site visits in the first week of June 1990, no oil was observed either contained within or stained on the booms, and during numerous overflights of these beaches no sheens were observed. The small quantities of oil that remained in the subsurface of these beaches in June 1990, therefore, appeared to be stable and not easily remobilized, which is consistent with other studies (NOAA 1990).

In general, oil was observed at greater depths on coarse-grained sediment (pebble-cobble-boulder) beaches than at locations where finer-grained sediments (sands and granules) were present. At the latter sites, the smaller interstitial pore spaces and the viscosity of the oil generally combined to limit penetration to depths on the order of 10 cm. An example of this condition is the upper intertidal zone of a sheltered beach in Herring Bay. Oil observed in Pit 3 at the site had penetrated to 12 cm (Figure 8, above). The limit of penetration coincided with a sediment change from mixed sand-pebble-cobble material to the same mixture plus gray mud. Field and laboratory studies have demonstrated that heavy crude oil does not

Figure 9

Subsurface Oil Changes Over Time/Sleepy Bay, Site AP-13

Pits dug on three different occasions at the same location at Sleepy Bay reveal changes in both beach surface elevations and subsurface oiling. The common datum for these pits is a fine grained, clean sand layer that limited oil penetration. Fall to winter 1989 wave action removed, reworked, and washed the pebble-cobble sediment cover, resulting in a reduced subsurface oiled layer (Photographs B-17 and B-18, on page B-6).



The datum used is the former seabed surface consisting of clean, well-sorted sand.

penetrate more than 1-2 cm where mud is present (Harper and Humphrey 1986). Pit 4 from the upper intertidal zone at the Herring Bay site provides an example of subsurface oil that resulted from burial of an asphaltic layer by a 10-centimeter-thick cover of clean sediment. TEH values from samples collected at the 20-25 cm depth layer in Pit 4 and from the top 10 cm in Pit 3 produced values of 1.4 and 2.4 percent oil-in-sediment by weight, respectively. Surface samples of TEH from Pits 2 (middle intertidal zone) and 4 produced values of 0.16 and 0.1 percent, respectively.

Results of reworking of subsurface oil were observed at Sleepy Bay (Figure 9, above; Photographs B-11 through B-18, on pages B-4 to B-6) where oil had penetrated the pebble-cobble upper intertidal zone to a depth of 60 cm (July 13, 1989). At 60 cm, the oil was prevented from penetrating farther by a zone of well-sorted sand (Photograph B-17, on page B-6; Figure 9, above). The sand appears to be the former nearshore seabed that was uplifted during the 1964 earthquake. A pit dug at the same location on Nov. 20, 1989 showed that:

- The top 25 cm of sediment had been eroded from the beach.
- The top 10 cm of the remaining oiled sediments had been reworked and cleaned.
- The zone of heaviest oil was a 25 cm thick layer.

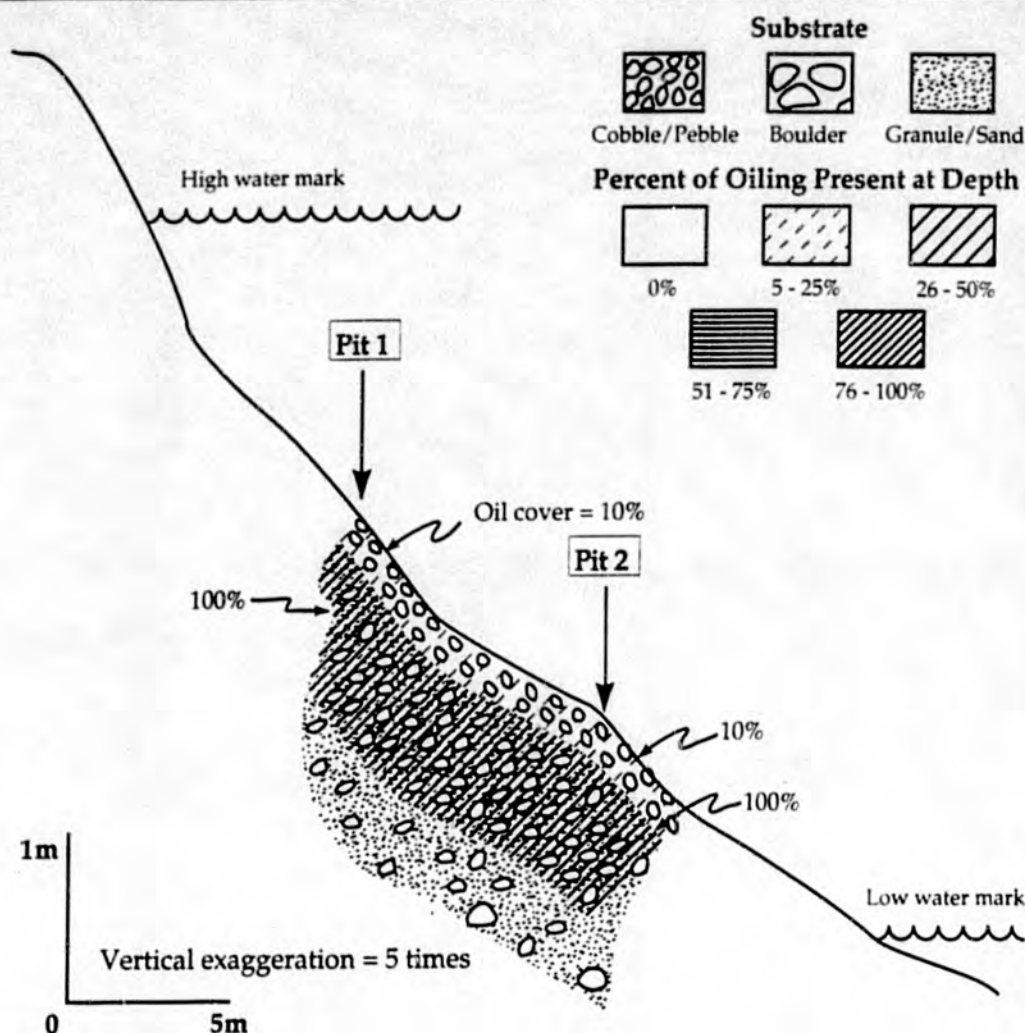
A pit dug on June 26, 1990 at the same location in the upper intertidal zone showed that the beach had been built up by constructive wave action almost to the same levels of the previous summer and that the oiled sediment zone above the clean sand was reduced to 10 cm in thickness (Photograph B-18, on page B-6; and Figure 9). Subsequent treatment activities, including tilling and bioremediation, addressed this oil lens.

Wave reworking also played a key role at study beach AP-1 on northeast Smith Island. This site was directly in the path of slicks from Bligh Reef, 35 km away. In April 1989, oil was observed to depths of at least 1 m. Surface washing during the summer of 1989 cleanup removed most of the surface and near-surface mobile oil, but deeper oil remained in September 1989. Storm wave action reworked sections of this beach to bedrock. This mechanical work exposed, washed, and abraded oil on the sediments such that no subsurface oil was observed in the intertidal sediments in trenches that were dug during a site visit on Nov. 20, 1989 in the central area of the beach near Transect 8, which is located on Figure D-1, on page D-4.

On some gravel beaches, sorting by wave action has produced a surface layer of coarse sediments, referred to as an armor layer, which overlies mixed fine and coarse gravel sediments. Armoring is very common on gravel coasts. Similar oil conditions with residues in the spaces between large surface sediments were observed at the "Arrow," "Metula," and "Nestucca" spill sites. The armor layer is often composed of uniform-size cobbles, such as at south Point Helen (AP-10). At this site, oil washed ashore, filled the large void spaces between the surface cobbles, and became pooled on top of the finer gravel sediments beneath the armor. This oil was then sheltered from wave washing and, with time, penetrated through the gravel to depths of several tens of centimeters. This subsurface oil was protected by the armor layer from wave action over the 1989-90 winter. Two pits dug in the upper intertidal zone at the south Point Helen site AP-10 in January 1990 showed oil to depths of 95 and 100 cm, below which no oil was present (Figure 10, on the next page). Prior to Jan. 19, 1990, oil had been removed from the surface armor layer of sediments on this beach by high energy waves during winter storms. Physical abrasion had cleaned the surface armor layer, but the depth of reworking and abrasion extended only to depths of 25-30 cm. TEH values from the 40 and 80 cm levels in Pit 2 produced values of 0.15 and 0.09 percent, respectively.

Figure 10
Subsurface Pit Sketch/South Point Helen, Site AP-10

A cross-section of the beach at Point Helen shows oil in sediments to a depth of 1 m in January 1990. Pooled oil was trapped between the cobbles of the surface armor layer and penetrated the gravel, where it remained protected from wave action.



Changes in Sediment TEH Data

Experience has shown that oil-in-sediment data from coarse-sediment (pebble-cobble) beaches do not conform to a normal distribution. Therefore, the monitoring program was designed to collect sediment samples for analysis only to provide general information on trends in the oiling conditions at the study sites. Data presented in this report and elsewhere (Jahns et al. 1991) indicate that oil-in-sediment concentrations have decreased with time at most sites, in both surface and subsurface data sets. This trend is consistent with other data collected by the monitoring program (i.e., surface oil cover, subsurface oil conditions) and with observations made during other survey programs.

More than 1,000 beach sediment samples from the study sites were collected and analyzed for hydrocarbon content. The sampling followed a systematic plan in which the same zones were sampled along the same transects on most occasions. The results provide a general indication of changes in oil-in-sediment concentrations through time. Two major features of the data set are particularly noteworthy:

Data from 12 sites show a general reduction of average TEH values.

Table 9
Summary of Average Surface Oil-in-Sediment from the Upper Intertidal Zone

Exposed Sites	Summer 1989 (mg/kg)	Fall 1989 (mg/kg)	Late Winter 1989-90 (mg/kg)	Summer 1990 (mg/kg)
AP-1	1,500	600	30	1,600
AP-8	3,600	700	900	N/A
AP-10	2,900	2,200	1,500	500
AP-12	2,800	1,100	1,200	300
Moderately Exposed Sites				
AP-5	2,700	N/A	50	250
AP-14	1,700	2,500	500	350
AP-15	2,500	N/A	350	1,000
AP-16	1,100	1,400	600	6,500
AP-17	850	2,700	20	150
Sheltered Sites				
AP-4	5,700	4,700	50	150
AP-6	N/A	8,400	10,000	4,000
AP-18	2,800	900	2,800	3,500

Note: Values expressed as percent in text. Example 600 mg/kg = 0.06%
N/A: Not available

- The samples were collected from study sites where the initial oil concentrations were high.
- Data from beaches composed of mixed coarse sediments are quite variable so only major trends are indicative of genuine change (Humphrey et al. 1990).

The data from the Kenai-Kodiak region are not reviewed in this report because the oil deposits outside of the Sound were very scattered and patchy, which means that individual data points are site specific and may not represent general trends.

In the Sound, the lower one-third of the intertidal zone was not heavily oiled initially. The 30 surface samples collected from this zone at different sites between May and August 1989 have an average value of 0.05 weight percent (equal to 500 milligrams (mg)/kilograms (kg); 1 percent = 10,000 mg/kg), whereas the mean for 78 samples from the middle and upper intertidal zone over the same time period is 0.17 percent. Average values do not reflect the wide range in the data set that is typical for this type of study; however, the analytical results for the Sound show reductions of oil concentrations over the winter period. Table 9, above, lists average TEH

values from surface samples collected in the upper intertidal zone, where oiling conditions were initially heaviest. This table includes only sites where a long-term data set is available.

The TEH values from three of the four exposed sites show decreasing concentrations over time. The values at six of the 12 sites – in particular, AP-12 (exposed), AP-5 (moderately exposed), and AP-4 (sheltered/moderate) – were clearly reduced, and the average of all upper intertidal zone samples from these 12 sites dropped from 0.26 to 0.15 percent between fall 1989 and late winter 1990. Similar trends are evident from the larger data set described by Jahns et al. (1991), which shows a decrease in the average from 0.36 percent to 0.16 percent over the 1989-90 winter months.

No subsurface samples were collected before September 1989. The results from the winter sample collection program show average subsurface TEH values of 0.35 percent for September 1989 and 0.10 percent for March 1990. This change indicates that winter wave action was able to rework, wash, and abrade the subsurface sediments on the study beaches. Additional reduction in oil quantities resulted from tidal pumping and biodegradation.

DISCUSSION

Most of the oil initially stranded on the Prince William Sound and Kenai-Kodiak shorelines was gone as of the September 1990 surveys, though remnants of oil remained, often as small patches in sheltered locations or as stains and coats on the sediments. All of the trends from the monitoring program show that the shorelines had recovered as a result of cleanup operations and natural cleaning. The lighter hydrocarbons, which are the most mobile and toxic components of crude oil, were removed by natural weathering, so the remaining oil cover was a stable and often tar-like substance. Subsurface oil was still present at only a few sites in the Sound as of September 1990.

The 1989 cleanup program focused on washing and collecting mobile oil from the shoreline. The success of this program is evident from the field observations on heavily oiled study beaches that were washed extensively. By September 1989, there was a significant decrease in surface oil cover at these sites. This change in surface oil cover understates the overall reduction in oil on the shoreline because it does not take into account the removal of mobile oil that was washed from the beaches. The general absence of asphalt pavements, which typically form on heavily oiled gravel beaches, is additional evidence of the effectiveness of the 1989 washing program.

Rates of natural cleaning varied, depending on the particular shoreline character and oil conditions at each site. The level of effort in the 1989 treatment program was also a factor in the changing oil cover. At AP-1, which was treated twice by large work crews over several weeks because of the sensitivity of nearby seal haulouts, the oil cover was reduced to 28 percent by September 1989. Similarly, a high level of effort at the Applegate Rocks haulout site removed virtually all of the surface and subsurface oil by May 15, 1989. At sites that were not extensively washed during 1989 (AP sites 2, 10, 11, 12, 13W, and 15) surface oil cover in August/September 1989 ranged between 37 and 63 percent, with a mean of 48. This indicates that the higher level of treatment effort contributed to cleaning the surface sediments.

In 1990 the focus of the treatment activities shifted to the oil residues. Most of the oil observed after the 1989-90 winter remained because it was out of reach of wave action or treatment activities. Oil residues were found beneath crevices, above the limit of normal wave action, and, at some sites, below the surface sediments. Manual removal, sediment (berm) relocation, and bioremediation were the primary techniques used in 1990 to pick up weathered oil, expose oiled sediments to wave action, and promote biodegradation, respectively. These programs were effective in further reducing the amount of remaining oil. Sediment removal was avoided because there is a paucity of material on the beaches of the Sound and little or no contemporary source of coarse sediments to the coastal zone. Experience with sediment removal following the "Arrow" spill, in a similar coastal environment, shows that removal of coarse material in this type of situation leads to beach erosion.

Subsurface oil was limited in extent because large portions of the coast are either bedrock outcrops or gravel (mixed sediment) beaches where penetration is restricted by the nature of the substrate. In particular, little subsurface oil was observed in sheltered environments because these beaches typically have a high proportion of fine-grained sediments. Burial of oil by sediment redistribution was observed at only a few locations. Burial of oil residues was not considered a systematic problem because this region had little influx of new sediment to the coastal zone and, therefore, few locations of sediment buildup. The few locations where subsurface oil remained after the summer of 1990 generally were sites where oil was able to penetrate into well-sorted pebbles and cobbles on exposed beaches. Also, at some locations with a surface layer of well-sorted coarse material, oil was concentrated between the sediments and protected from summer wave action by the surface armor layer. This oil was able to seep into the subsurface material and some of this oil remained there protected by the surface (armor) layer from subsequent winter wave action.

The trends observed at the study sites were confirmed by ground, boat, and helicopter inspections of other sections of coast over the study period. The surface oil-cover changes are well illustrated in the transect maps. The oiling trends depicted in the maps, and quantified in the tables and graphs, probably underestimate changes that took place over 18 months. The study sites selected, for the most part, were beaches with an initially heavy concentration and a wide band of oil. These beaches were the most difficult and slowest to clean, either by man or nature.

A reconnaissance of the Northwest Bay and Upper Passage coastline during the second week of January 1990 marked a distinctive turning point in documenting natural cleaning in these sheltered environments because, for the first time, extensive sections of the previously oiled intertidal zone were noticeably oil-free. These shorelines had been washed and most of the mobile oil removed throughout the summer of 1989, leaving a coat or stain on bedrock and sediments. The area had not been visited for six weeks before January 1990, and the changes in surface oiling were obvious and widespread. The natural cleaning of oil residues from these sheltered, low wave-energy environments occurred much more rapidly than expected. Laboratory studies point to the role of physico-chemical weathering as a significant factor in the natural removal of this residual oil (Jahns et al. 1991). This natural cleaning process probably would not have been effective with heavy concentrations of residual oil.

The observed changes in surface oil cover document the initial changes that were due to the 1989 treatment program. During the winter of 1989-90 wave action was the primary process by which exposed shorelines were cleaned. At the same time, natural removal of oil was taking place in sheltered environments due to biodegradation and to the interaction of the suspended sediments and seawater with the surface of the oil to form solid-stabilized emulsions (Bragg et al. 1990). These bio-physical weathering processes were more important in sheltered environments due to the diminished role of wave action.

Beach elevation transects illustrate the effects of winter storm wave action on exposed, and some relatively sheltered, sites. Winter erosion combed down, reworked, abraded, and washed the sediments to depths of more than 1 m at some sites, and constructive spring and summer wave action subsequently returned clean sediments to the beaches. The winter months from January 1990 onward were relatively free of severe storms, as is common in this region. Hence, overall levels of late winter and spring wave energy at the shoreline were lower than in the early winter (September to December 1989).

Detailed analysis of the transect data shows clearly that oiling was initially less extensive in the lower one-third of the intertidal zone, and that through time the remaining surface oil was concentrated on the uppermost sections of the shore. This is significant on most shoreline types, including gravel beaches, because the biological communities are richest in the lower intertidal areas.

Oil-in-sediment (TEH) data do not always exactly reflect observed changes at most sites. This discrepancy has been recognized in previous studies and is a result of the difficulty in sampling coarse-grained sediments. Oil concentration data have been found to be extremely variable in mixed and coarse-grained sediment environments. This type of data best represents oiling conditions for sand beaches (Humphrey et al. 1990). Two trends, however, can be deciphered from the Sound data: (1) The lower intertidal zone did not initially, or subsequently, have high oil-in-sediment concentrations; and (2) there was a general reduction of oil-in-sediment concentrations over the 1989-90 winter months (Jahns et al. 1991).

The intertidal ecology program used photographic surveys of key surface organisms on 44 oiled sites where 183 transects in total were sampled. Sites that were surveyed in September of 1989 and 1990 were compared to assess the rate of biological recovery during the year. These sites were then compared to unoiled reference sites surveyed in September 1990 to evaluate the extent of recovery. The comparisons reveal that the distributions and abundances of key organisms on most oiled sites by September 1990 were not substantially different from those on the unoiled reference sites. Lower rates of biological recovery appear to have occurred on some heavily oiled sites that were not extensively treated to remove bulk oil in 1989.

The data from the monitoring sites clearly demonstrate the reductions in the surface oil cover over the 18-month study period. The fact that significant reductions occurred over the 1989-90 winter on both exposed and sheltered sites indicates that other processes, in addition to wave action, can be important in the natural cleaning of the oiled shorelines. Greatest emphasis is given to the oil cover data; nevertheless, general trends are evident in other data sets, including the reduction of subsurface oil and the natural recovery of key intertidal species.

CONCLUSIONS

Program

- The study sites focused on beaches that were initially heavily oiled, thus biasing the study toward worst-case conditions. Therefore, the amount of oiling discussed in this report is not representative of shoreline conditions throughout the region. However, one would expect to find less oil on most other shorelines.
- The monitoring program required a considerable commitment, but as a result, this is the best-documented and most-studied spill to date.

General Observations

- Significant reductions of oil conditions have been documented.
- The 1989 treatment program accelerated the rate of recovery, so most shorelines were free of oil after 18 months.

Oil Cover

- The combined oil cover for the Sound study sites dropped from 46 percent of the total observed area in May 1989 (six sites only) to 39 percent in August 1989, to 12 percent by January 1990, and to less than 2 percent by September 1990.
- The original oiled area on two of the exposed Kenai-Kodiak sites with wide-band oil was reduced to 7 percent at AK-4 by January 1991 and to less than 1 percent at AK-5 by March 1990.
- Analysis of transect data showed that oil cover changes were related to treatment activities and to wave action. For example:
 - The first treatment phase at the northeast Smith Island site (AP-1) reduced the oil cover from 100 percent to 79 percent; the second treatment further reduced the cover to 44 percent and winter wave action reduced it to 1 percent.
 - At the moderately exposed AP-4 site in the Sound, most of the oil cover change (from 33 to 12 percent) occurred over a four-week period in mid-winter.
- Rates of natural cleaning varied from site to site, depending on site exposure and the coincidence of onshore storm-generated waves with the fetch window of a beach.
- The removal of mobile oil by the 1989 washing program enhanced biodegradation and physico-chemical weathering.

Subsurface Oil

- Subsurface oil was not common on the shorelines affected by the spill, and few beaches contained any oil within the subsurface sediments as of September 1990.
- Oil penetration was largely restricted to depths on the order of 10 cm because of the presence of relatively fine-grained subsurface sediments on the majority of beaches in the study region. Bedrock outcrops form the shoreline or underlie a coarse-sediment veneer on 70 percent of the oiled coasts of the Sound.
- At a few locations where beaches are composed of coarse sediments, the oil had penetrated as much as 1 m deep; these beaches are typically exposed, high wave-energy environments and, in some cases, were reworked to depths of 1 m during the winter (for example, at AP-1).
- By June 1990 the remaining subsurface oil appeared stable, releasing neither oil nor sheens to the nearshore waters (NOAA 1990).

Sediment TEH Data

- The results from oil-in-sediment studies on mixed or coarse-grained sediment beaches provide a highly variable data set.
- There is a trend of oil concentration reduction through time that is consistent with all other field observations and data sets.

Beach Changes

- Wave action caused sediment reworking and redistribution, with washing and abrasion of oiled sediments, on most beaches.
- Wave activity was greatest on exposed Kenai-Kodiak beaches, with documented erosion and deposition greater than 1 m at some sites.
- Similar erosion was recorded in parts of the Sound, with reworking down to 1 m at exposed study sites.
- Beaches rebuilt during the spring of 1990 at most locations as constructive waves returned sediments to the intertidal zone.
- Sediments were also reworked on sheltered and moderately exposed beaches.

Winter Winds and Waves

- The dominant and prevailing winds in the Sound were out of the eastern quadrant from September 1989 to June 1990.

- Approximately 18 storm events occurred during this time; six major storms occurred before January 1990, with peak winds in excess of 85 km/hr or a daily average wind speed greater than 40 km/hr.

Biological Observations

- Photographic monitoring of surface biota over a one-year period to September 1990 shows that at most oiled study sites the abundance and distribution of key intertidal species were not substantially different from those at non-oiled sites.
- Ecological recovery appeared to be enhanced at some sites where 1989 treatment activities (flush and flood) were able to remove the majority of the bulk oil.

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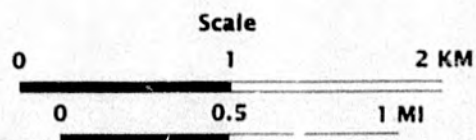
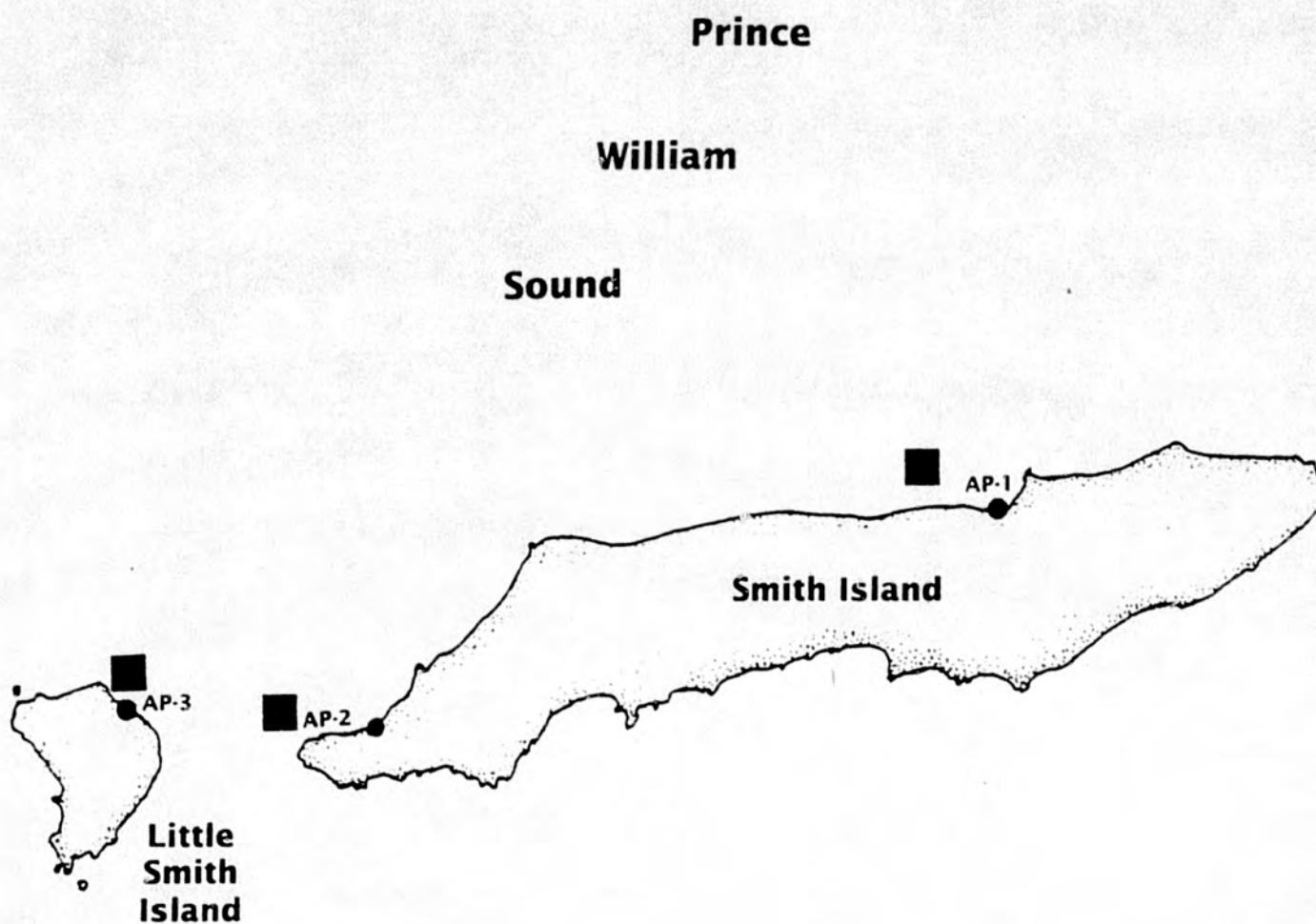
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APPENDIX A

Site Location Maps

Twenty-eight locations were surveyed beginning in the spring and summer of 1989 to document changes in oil cover through time. Figures A-1 through A-9, on the following pages, show the location of these sites on detailed maps. Overview maps are shown in Figures 2, 3, and 4, on pages 6, 7, and 8.

Figure A-1
Site Location Map/Smith Island



Wave-Energy Environment

-  Exposed = Unprotected shoreline and large fetch area
-  Moderate = Some unprotected shoreline and intermediate fetch area
-  Sheltered = Protected shoreline and/or short fetch area

Figure A-2
Site Location Map/Knight Island

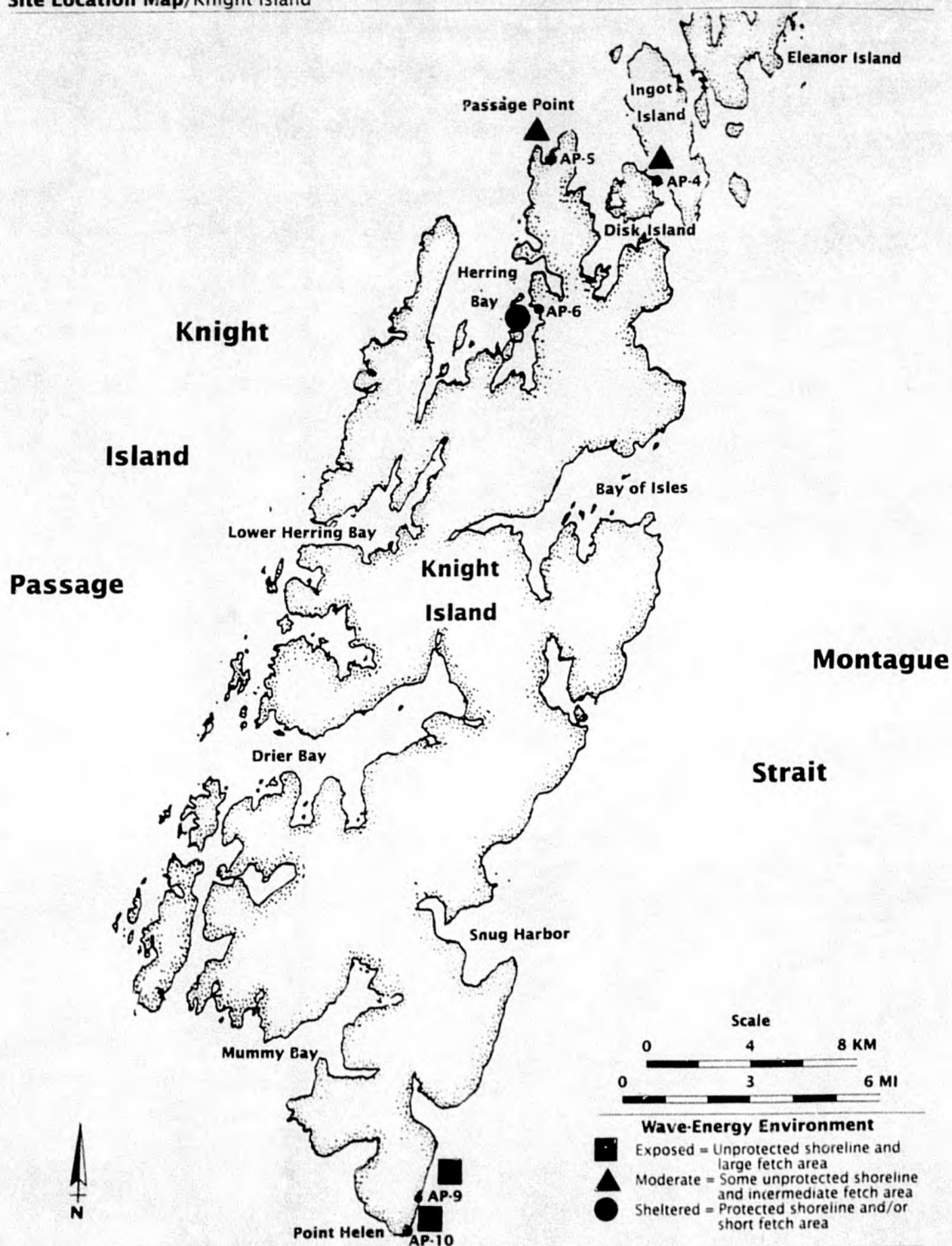


Figure A-3
Site Location Map/Green Island

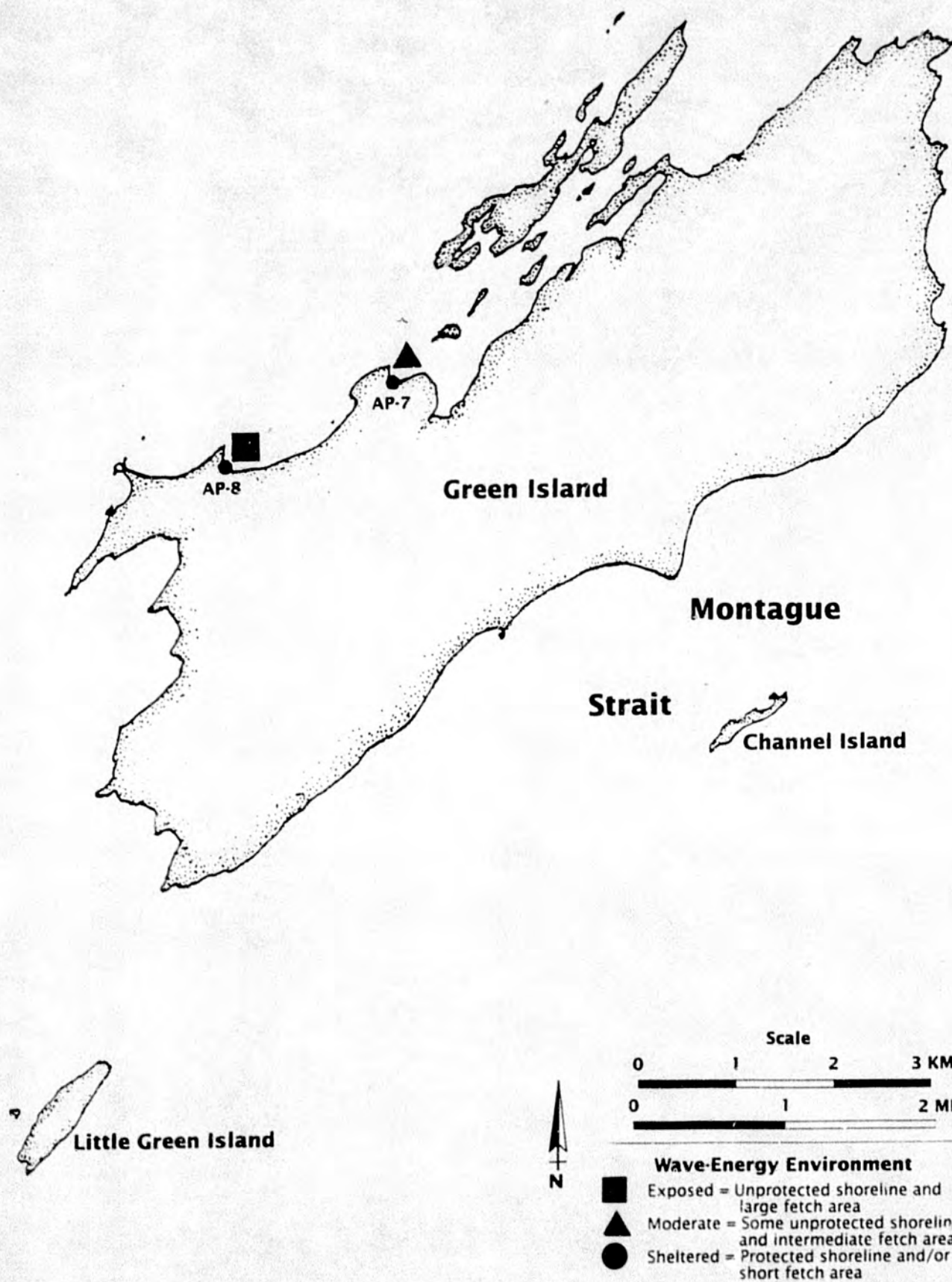


Figure A-4
Site Location Map/Latouche Island

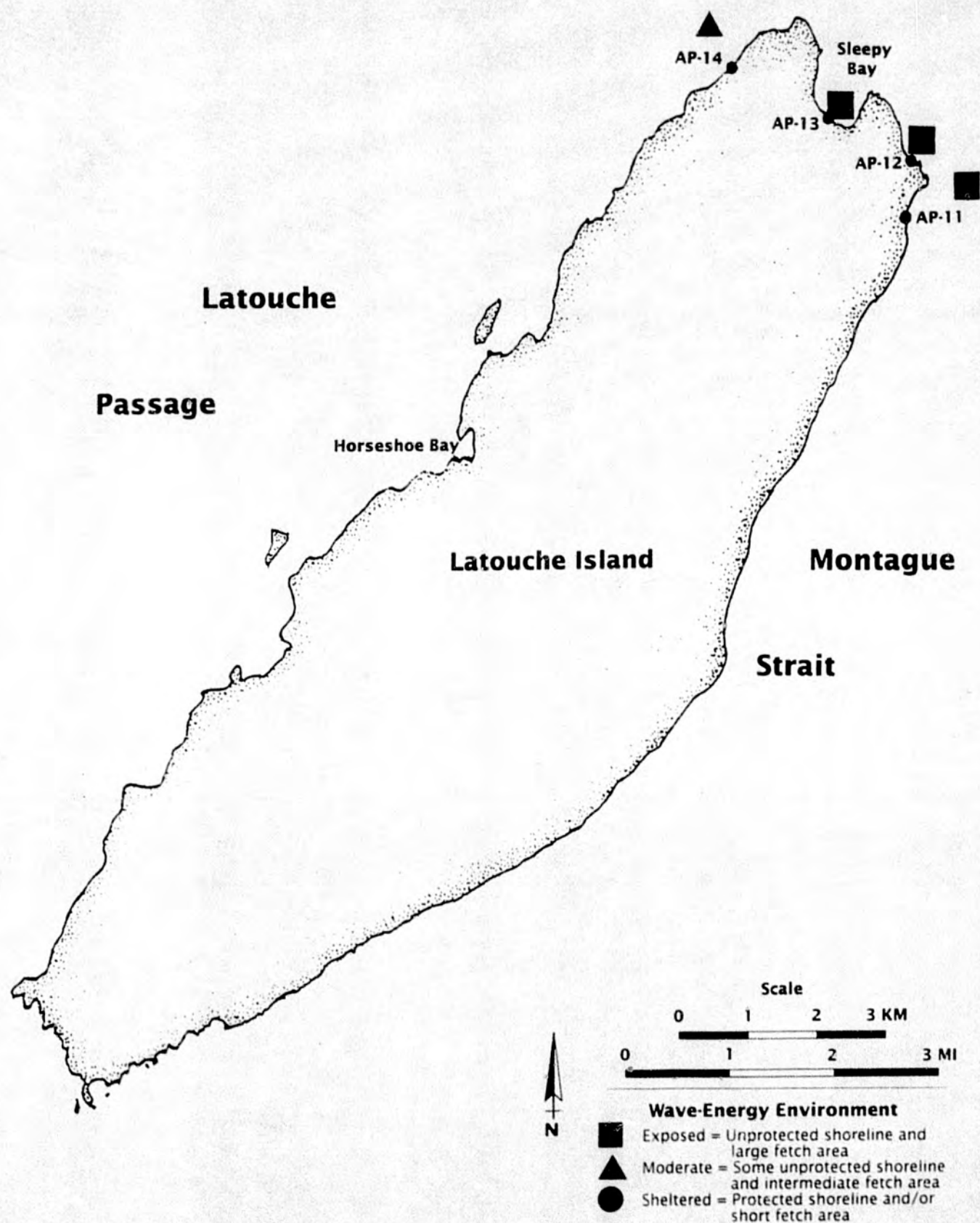


Figure A-5
Site Location Map/Evans Island

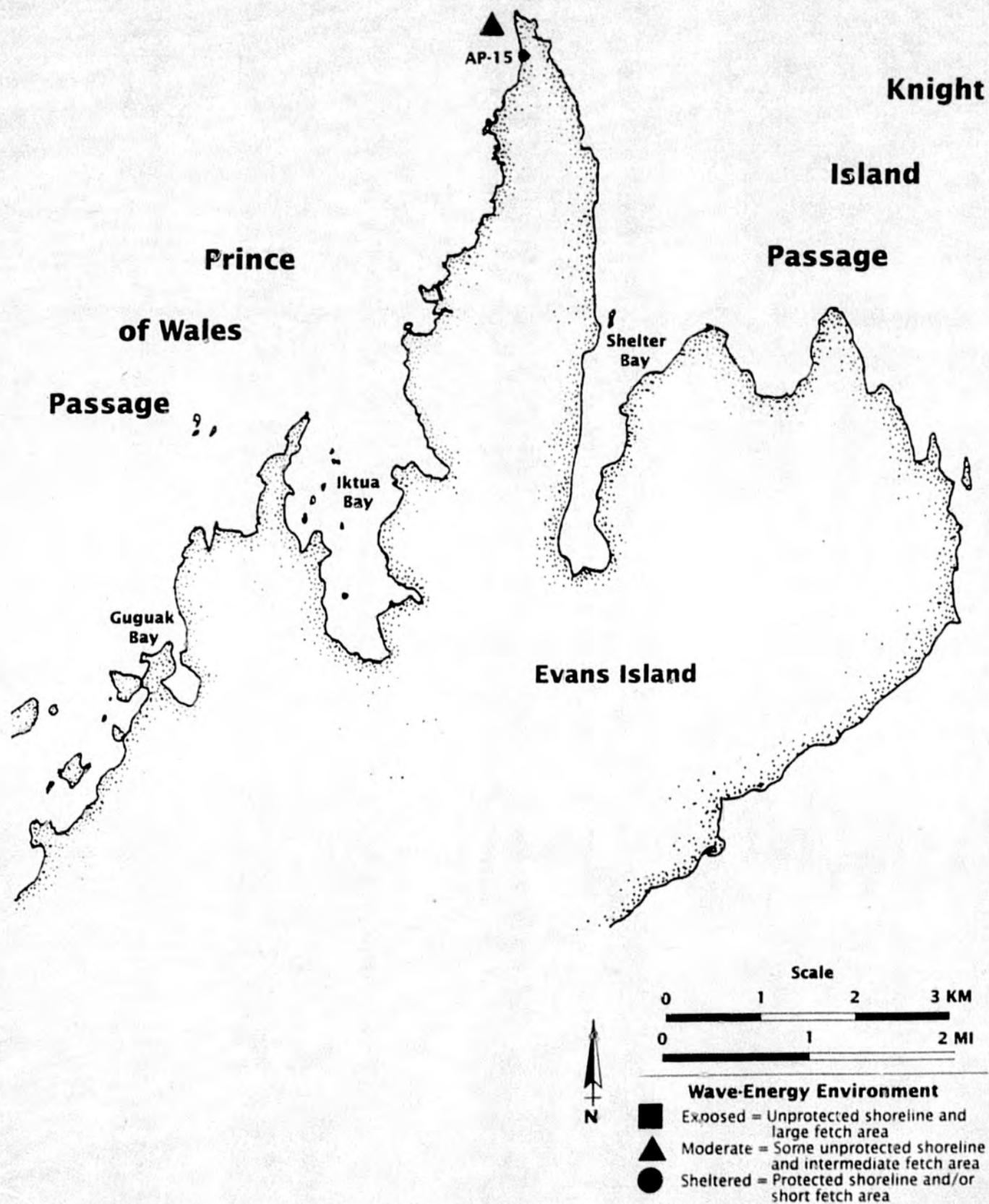
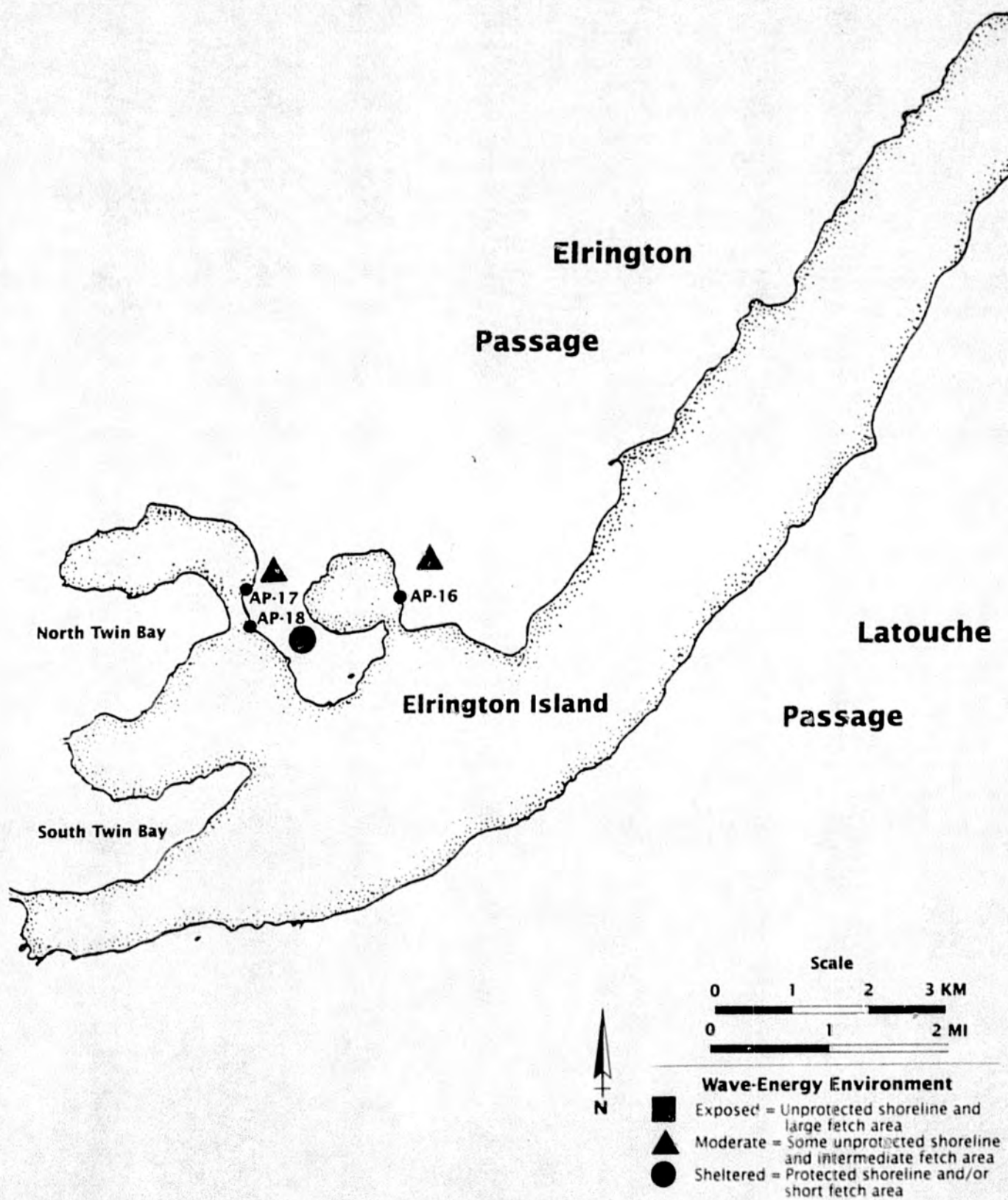


Figure A-6
Site Location Map/Elrington Island



8-V Figure A-7
Site Location Map/Kenai Peninsula

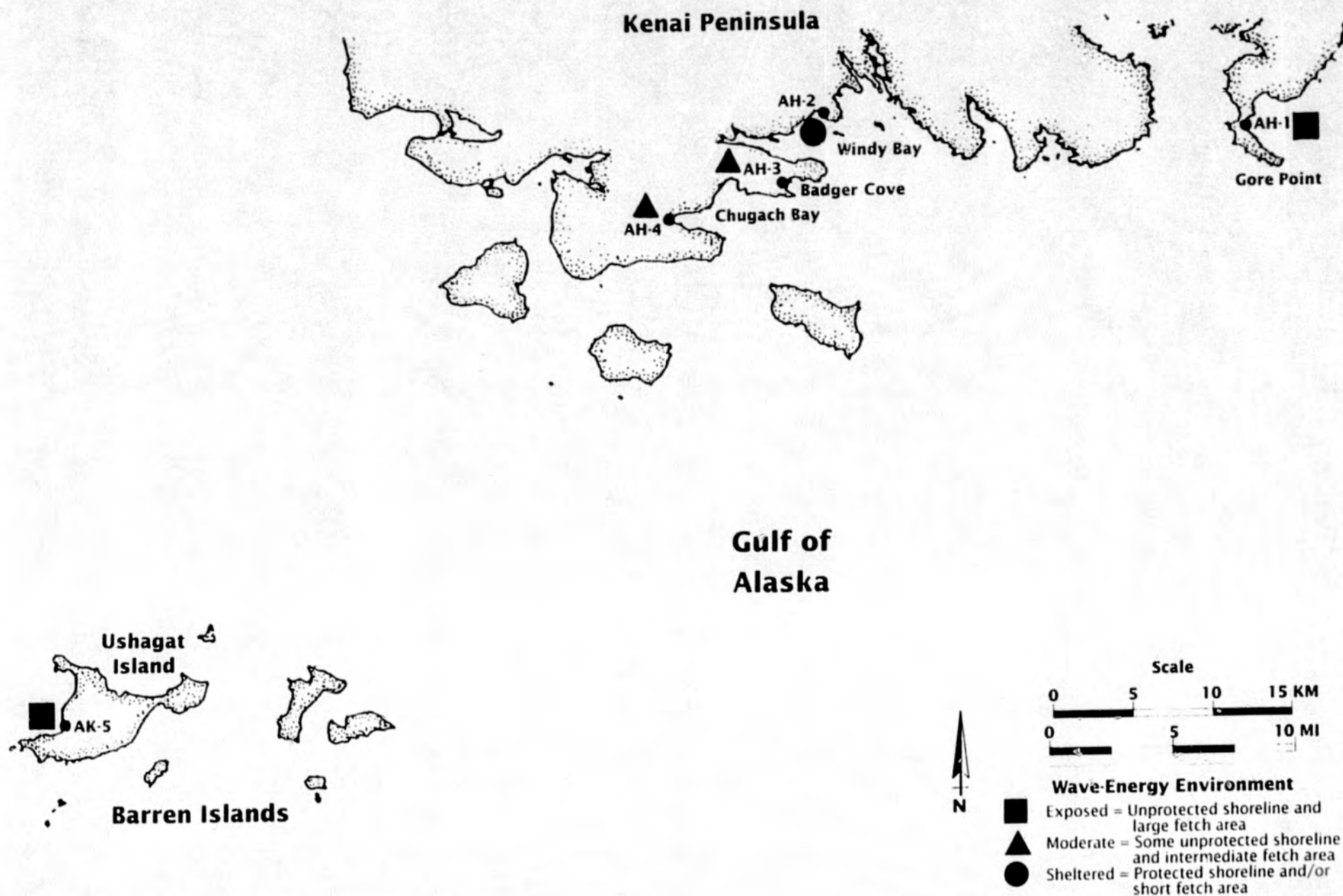


Figure A-8
Site Location Map/Afognak Island

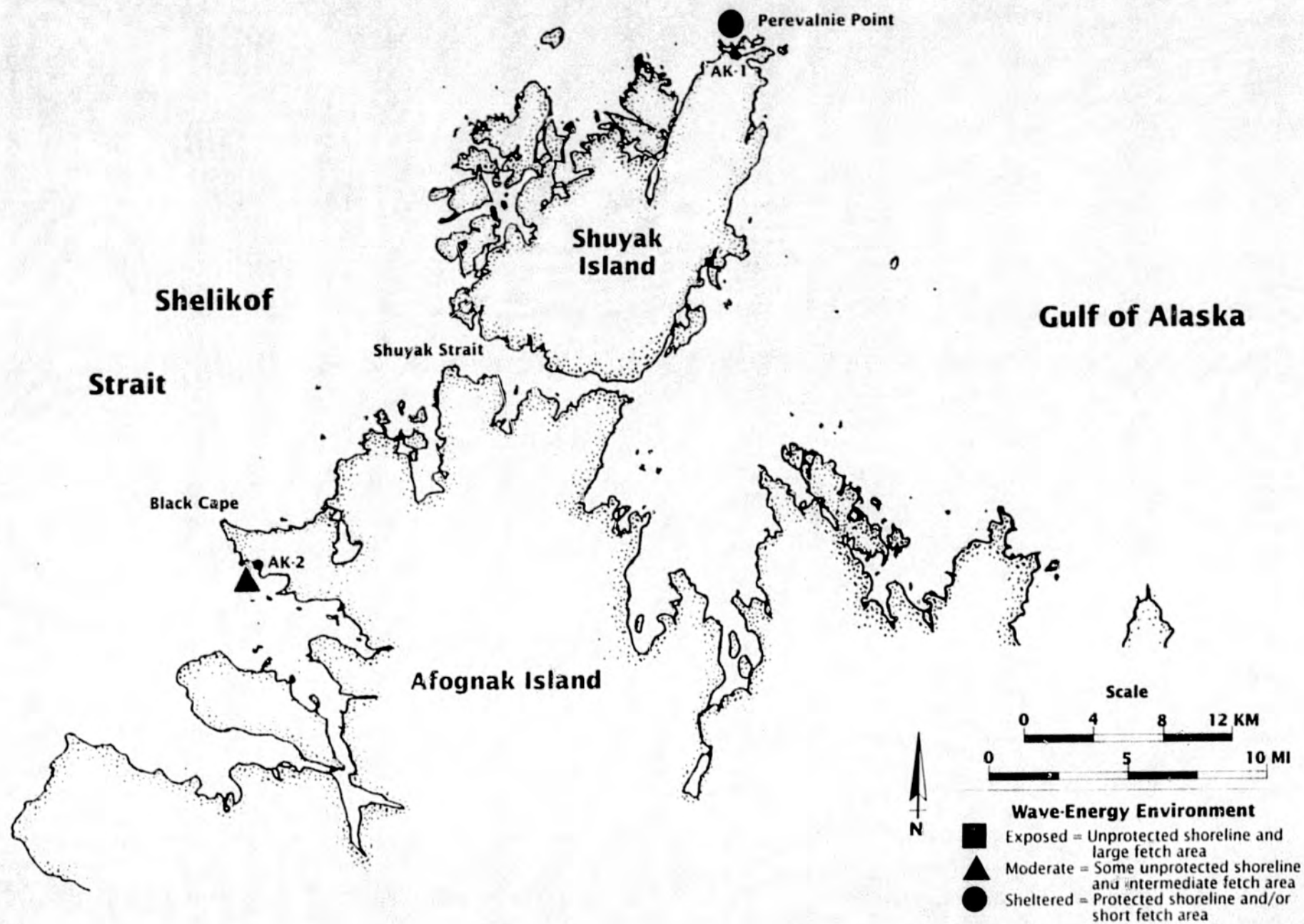
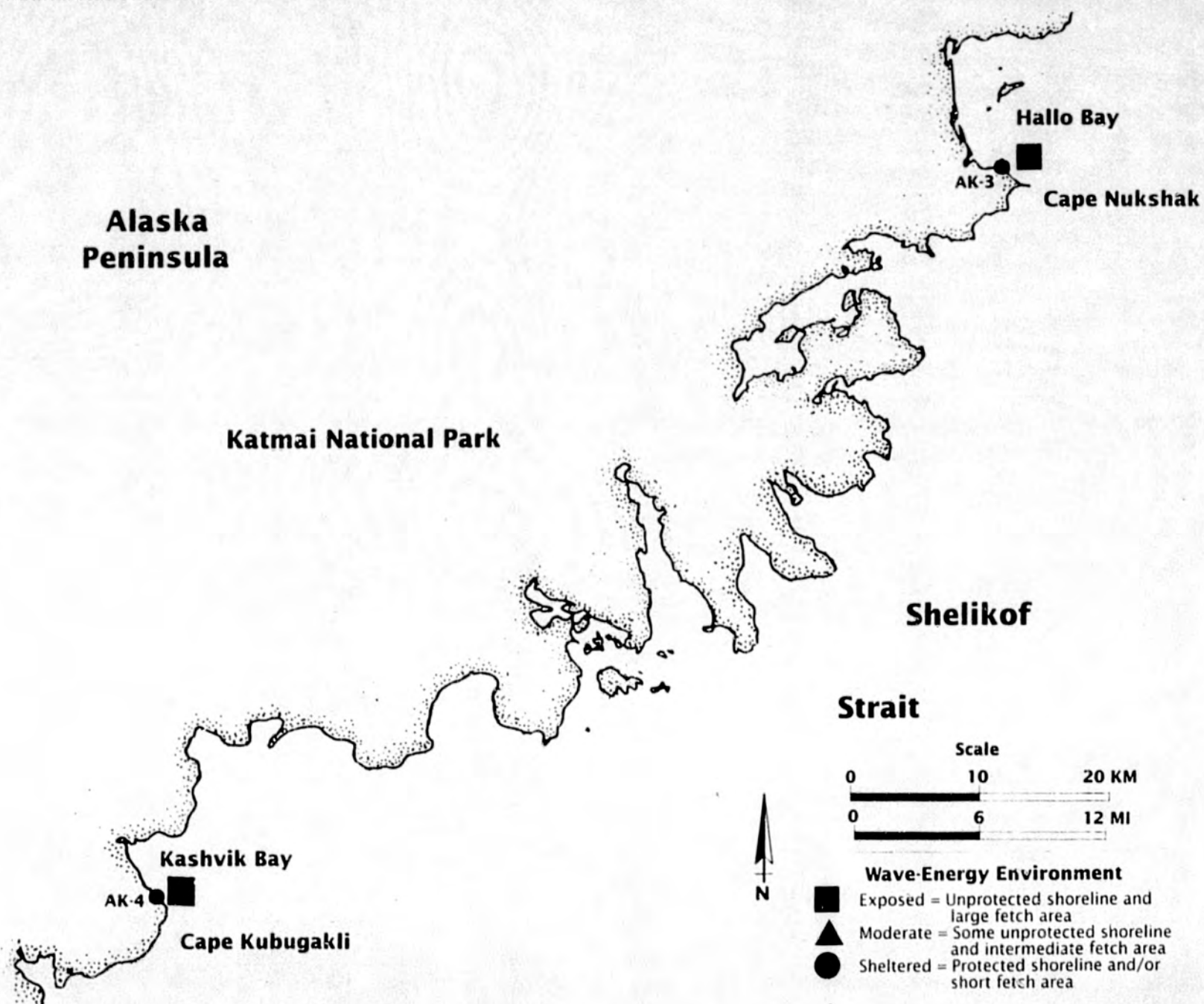


Figure A-9
Site Location Map/Katmai National Park

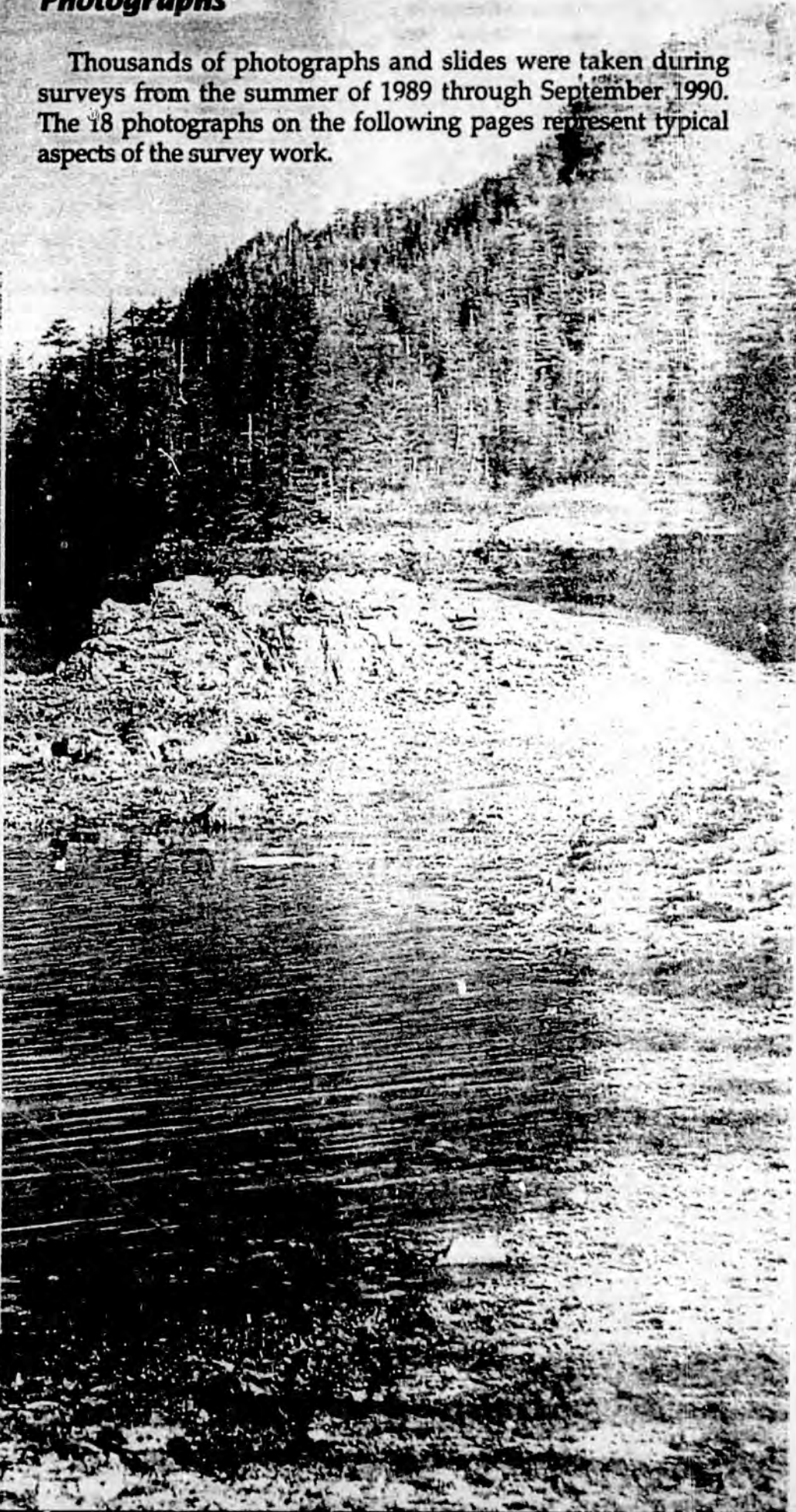
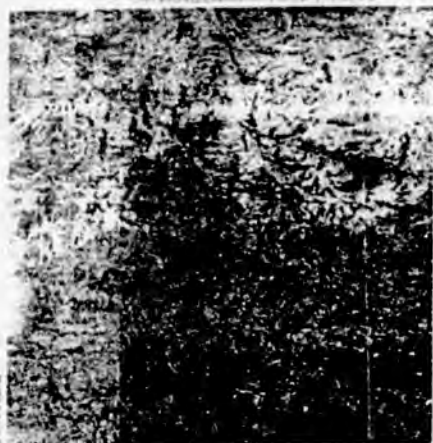




APPENDIX B

Photographs

Thousands of photographs and slides were taken during surveys from the summer of 1989 through September 1990. The 18 photographs on the following pages represent typical aspects of the survey work.



Photograph B-1- This beach and rock headland on southern Lone Island typify many of the shorelines in the Sound. This June 1990 photograph shows dark bands of lichen (marked by a bracket to the right of the photograph) and patches of mussels (marked by an arrow), not oil, on the rocks. Such features are found widely throughout the Sound. This site was oiled in 1989 but clean by the time of this visit. ►



B-1

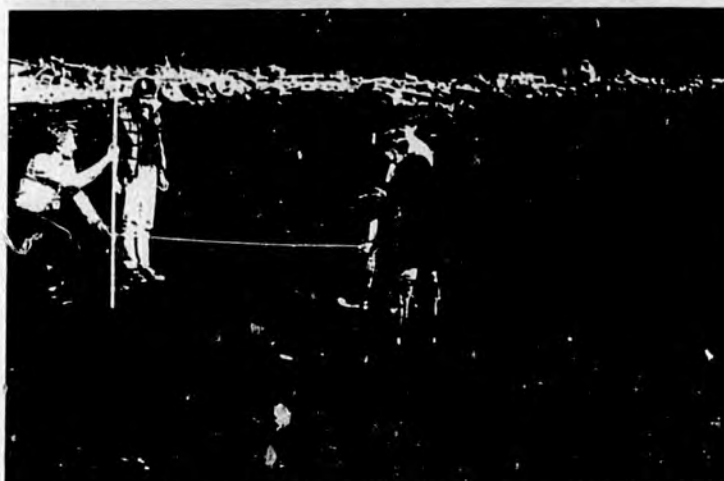
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Photograph B-2- This general view shows a rugged, exposed, high wave-energy coastline on the Kenai Peninsula on a calm summer day. The photograph was taken at northeast Black Bay on June 27, 1989. ►



B-2

Photographs B-3 and B-4- Survey teams worked along transects oriented approximately perpendicular to the shoreline. Field activities included surface and subsurface oil cover observations, photographic and videotape records, sediment sampling, and beach elevation profiles. Beach elevations were usually surveyed using the Emery method by taking readings every 2 m along a transect (Photograph B-3, taken at Ingot Island, site AP-4, on Sept. 15, 1989). Pits were dug to examine the extent of subsurface oiling (Photograph B-4, taken at west Knight Island, March 17, 1990). ►



B-3



B-4

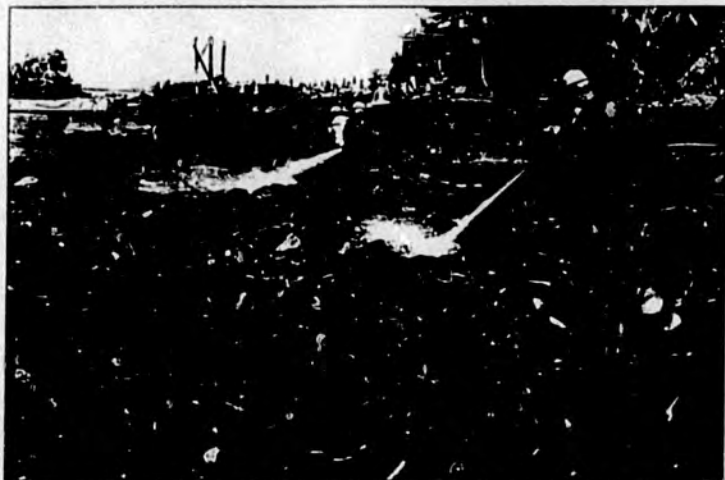
Photographs B-5 and B-6—
 These photographs show
 views to the west of the
 beach at site AP-1 on
 northeast Smith Island.
 Photograph B-5, taken on
 May 2, 1989, shows the
 initially heavily oiled beach.
 The same beach was
 virtually clean by June 12,
 1990 (Photograph B-6). The
 arrow indicates the location
 of closeup Photographs B-9
 and B-10.



B-5



B-6



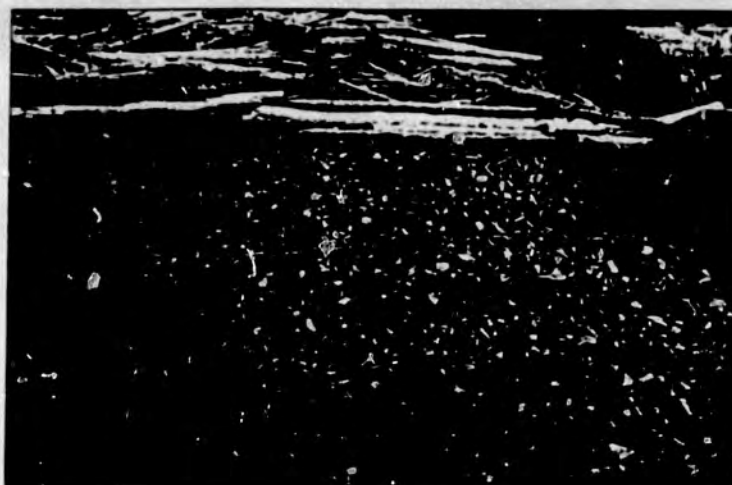
B-7

Photographs B-7 and B-8—
 As in Photographs B-5 and
 B-6, the changes in surface
 oiling are clearly evident
 between May 2, 1989 (B-7)
 and April 10, 1990 (B-8) in
 these views to the east of
 the beach at site AP-1 on
 northeast Smith Island.



B-8

Photographs B-9 and B-10—
 Winter wave action resulted
 in 4 m of lateral erosion and
 1 m of vertical erosion
 between the time of these
 two photographs, which are
 closeup views of the west
 end of the beach at site AP-1
 on northeast Smith Island on
 April 19, 1989 (B-9), and on
 April 10, 1990 (B-10).



B-9



B-10



B-11

Photographs B-11 and B-12—
 Aerial views of Sleepy Bay
 site AP-13 at northern
 Latouche Island show the
 changes in surface oiling
 along the western portion of
 the site from May 9, 1989
 (B-11) to June 12, 1990
 (B-12). The cross indicates
 the location of closeup
 Photographs B-15 to B-16,
 and the arrow locates
 Photographs B-17 and B-18.



B-12

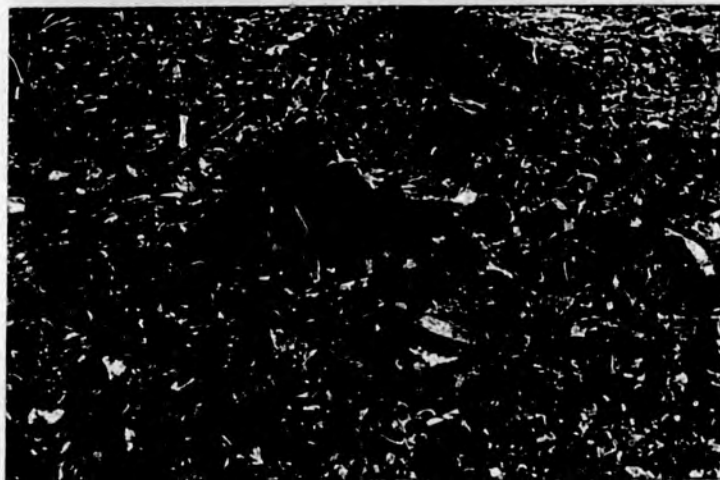
Photographs B-13 and B-14—
 Views of the east end of the
 beach at Sleepy Bay site AP-
 13 at northern Latouche
 Island show the decrease in
 surface oil cover from May
 9, 1989 (B-13) to March 15,
 1990 (B-14).



B-13



B-14



B-15

Photographs B-15 and B-16—
 Closeup photographs of the
 oiled sediments at the east
 end of Sleepy Bay at site
 AP-13 (Photograph B-13)
 show the significant
 changes in oil cover and
 character that occurred
 between May 9, 1989 (B-15)
 and March 15, 1990 (B-16).

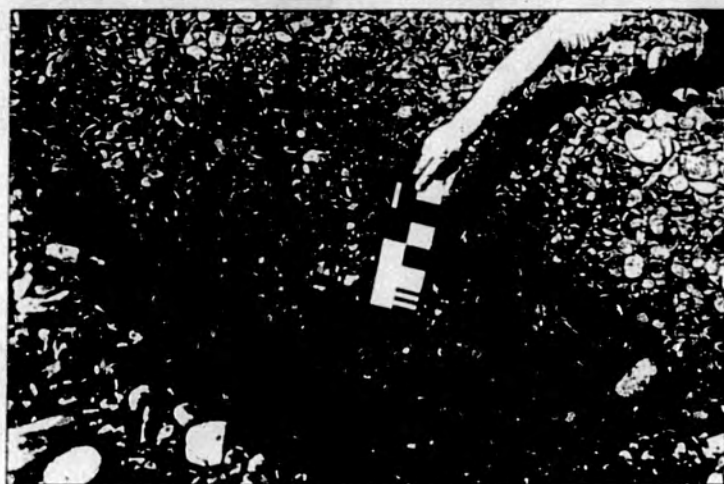


B-16

►
Photographs B-17 and B-18—Pits dug July 13, 1989 (B-17) and June 26, 1990 (B-18) in the same location at Sleepy Bay site AP-13 show changes in subsurface oiling (see Photograph B-12 for location). The dark interval (arrow) is a clean sand layer that limited the downward movement of oil. This sand layer was probably the former seabed, which was elevated during the 1964 Alaska earthquake. The length of the scale is 30 cm (approximately 12 inches). Sketches of these two pits are shown in Figure 9.
►



B-17



B-18