Exxon Valdez Oil Spill
Restoration Project Final Report

1993 Shoreline Oiling Assessment of the *Exxon Valdez* Oil Spill

Restoration Project 93038
Final Report

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Study History: This project was designed to address remaining shoreline oil from the *Exxon Valdez* oil spill. The project was in response to public requests to continue monitoring of affected shorelines and to continue cleanup of high-priority sites identified by the public. This project had four objectives that were not necessarily related: (1) monitoring of sites; (2) assessing the changes in subsurface and surface oiling; (3) investigating community complaints; and (4) remediation. After assessing the time and resources available, staff narrowed the scope of the remediation effort to manual cleanup that could be accomplished during the site surveys. An initial draft report titled 1993 Shoreline Assessment by E. Piper and J. C. Gibeaut was issued in April 1994 . A five-volume data report was also completed in 1994 by Gibeaut and colleagues. A poster was presented and an article was published in 1995 regarding this project (Gibeaut, J. C. and E. Piper, 1995. Shoreline oil from *Exxon Valdez*: change from 1991 to 1993, Proceedings, 1995 International Oil Spill Conference, American Petroleum Institute, Washington, D.C.. p. 972-973.).

Abstract: During the summer of 1993, the Alaska Department of Environmental Conservation surveyed 59 shoreline sites in Prince William Sound, Alaska that were oiled by the March 1989 *Exxon Valdez* oil spill. The data describe the oil's visual properties and extent. Comparisons of commonly measured locations through the years provide estimates of oil reduction.

From 1991 to 1993, the amount of asphalt, surface oil residue, and surface mousse decreased by about one-half. This decrease was largely caused by manual removal and raking. Subsurface oil reduced by more than one-half. Sites that were tilled or from which oiled sediment was removed showed a greater decrease than sites not treated. By 1991, and still in 1993, most of the surface oil resided between mid- to upper intertidal large boulders and in bedrock fractures along low-, moderate- and even high-energy shorelines. Asphalt was also present on the upper intertidal surfaces of sheltered pebble and cobble beaches and bedrock. Recalcitrant subsurface oil was typically below clean surface sediments along boulder-dominated limbs of pocket beaches and in bedrock- and boulder-sheltered areas along otherwise high-energy shorelines. In some areas, sediment surface armor has prevented natural or unnatural physical removal. Subsurface oil also remained in some very-low wave energy settings. Future rates of oil removal will likely be less because of natural entrenchment and no likely effective cleanup.

In 1993, we measured 27,000 m^2 of beach affected with surface oil. The oil occurred in 217 scattered locations along a total of 4.8 km of shoreline; some locations sheened. We also measured a total of 2,041 m^3 of subsurface oiled sediment in 109 locations including 738 m^3 of oil-saturated sediments. The total length of shoreline contaminated with subsurface oil was about 7 km. These are minimum values for oil remaining in Prince William Sound because not all of the oil was surveyed.

Key Words: *Exxon Valdez*, Prince William Sound, shoreline oiling, oil spill, cleanup

Project Data: Field notes, maps, photographs, and descriptions and analyses of each survey site are available in a five-volume data report titled Gibeaut, J. C., E. Piper, D. Munson, J. Matthews, M. Profita, and C. Crosby, 1994, 1993 Shoreline assessment data report: volume 1 (introduction and ground surveys AE005A through EV036A), volume 2 (ground surveys EV037A through KN136A), volume 3 (ground surveys KN209A through LA015D), volume 4 (ground surveys LA015E through TB004A), volume 5 (transect surveys): *Exxon Valdez* Oil Spill Restoration Project (Restoration Project 93038), Alaska Department of Environmental Conservation, Juneau, Alaska.1993 Shoreline Assessment Data Report. These reports are available at the Oil Spill Public Information Center which is part of the Alaska Resources Library & Information Services, 3150 C Street, Anchorage, Alaska 99503; 907-272-7547; http://www.alaska.net/~ospic.

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EXECUTIVE SUMMARY

Introduction

The *T/V Exxon Valdez* ran aground on March 24, 1989 and spilled 11 million gallons of Alaska North Slope crude oil into Prince William Sound, Alaska. By the end of September 1989, hundreds of kilometers of shoreline in Prince William Sound had been contaminated by varying amounts of oil. Since the first summer of the spill, response teams have repeatedly surveyed the shorelines to map the distribution of visible oil in the intertidal and supratidal zones. These shoreline oiling surveys were specifically designed to support the cleanup effort and the information was used to make decisions on the type of treatment, if any, to be performed at particular sites. The surveys, however, also provide data on the effects of cleanup and physical setting on the rate of removal of shoreline oil. The 1993 shoreline survey described in this report continues the time series begun in 1989 and covers 45 sites in Prince William Sound and 2 sites in Tonsina Bay on the Kenai Peninsula. Twelve detailed transect surveys were also remeasured in 1993. In addition to summarizing 1993 shoreline oiling conditions, this report makes comparisons with the 1991, and 1992 surveys. A review of the history of shoreline oiling from the *Exxon Valdez* and comparison with other spills is also included. Appendix A is a discussion of management, policy, and community issues related to the survey itself and to the remaining shoreline oil in Prince William Sound. For a detailed site-by-site presentation of the data discussed in this report, the reader should refer to the 1993 Shoreline Assessment Data Report Volumes One through Five. These volumes may be obtained from the Oil Spill Public Information Center in Anchorage, Alaska (3150 C Street Anchorage, AK 99503; 907-272-7547; http://www.alaska.net/~ospic.

During the first summer of the spill, surface oiling decreased by about 50%, but significant subsurface oil remained at the end of the first cleanup season. During the first winter, surface oil reduced again by 50% to 80% with sheltered locations improving the least but still by surprisingly large amounts given the lack of wave energy. Subsurface oil also significantly decreased over the first winter showing a reduction of about 40% to 88%, but with little reduction in sheltered settings. By spring 1990, the greatest and most difficult problem was subsurface contamination that actively sheened, and the cleanup operation addressed this with mechanical tilling, berm relocation, and oiled sediment removal. During the 1990 cleanup and the winter of 1990/91, there was more improvement in surface oiling, but the amount is harder to estimate. By the spring of 1991, probably less than 10% of the initially oiled shorelines still contained surface oil, and the oil occurred chiefly in scattered locations between surface boulders and bedrock and in bedrock fractures. Surface asphalt in sheltered locations also remained. Despite the successes of mechanical tilling and berm relocation during the 1990 cleanup season, subsurface oil remained in 1991 in some high-energy gravel and low-energy rubble shorelines. This subsurface oil was a concern, and Exxon addressed it late in the 1991 cleanup season with mechanical tilling and berm relocation where sedimentological and ecological conditions allowed.

Objectives

The overall goal of the 1993 shoreline survey was to determine if shorelines in Prince William Sound and on the Kenai Peninsula had recovered sufficiently to facilitate normal shoreline activities. Specific objectives included the following: (1) survey selected shorelines for oiling; (2) determine if resource uses are affected by oiling or spill-related activities; (3) Perform light-duty manual treatment to improve resource uses; (4) write work orders for local crews to perform additional cleanup, if necessary; and (5) assess changes in oiling over time, as possible.

Methods

The 1993 shoreline assessment team conducted ground surveys at 45 sites and transect surveys at 13 sites in western Prince William Sound from Perry Island in the north to Latouche and Elrington Islands in the south and in Tonsina Bay on the Kenai Peninsula. The team looked at an additional 20-25 sites requested for survey by the public. All sites were originally oiled in 1989 following the *Exxon Valdez* oil spill. The 1993 field work began June 4 and ended September 27.

This survey had the same design as previous Exxon and inter-agency intertidal and supratidal shoreline surveys. Workers qualitatively described oiling character and concentrations using common techniques, criteria, and definitions used since 1990. Surveyors dug pits in the beaches and turned over cobbles and boulders to reveal hidden oil. After the beaches were dug and a general reconnaissance made, workers then documented the oil distribution on field maps. Areas of distinct oiling were measured with a tape and visual estimates made of the percentage of cover of oiling within the area. Shorelines were visited within two hours of low tide and always when the tide level was lower than plus two meters. At some locations workers conducted transect surveys along which measurements of beach topography, sedimentology, and oiling were made.

Survey team members worked together to calibrate their judgments on oiling classifications and percent coverage estimates. All survey work was done as a team with constant interaction between surveyors. All surveyors had worked on the spill since 1989 and were experienced observers of oiling in Prince William Sound. In addition, Exxon assigned two observers with extensive shoreline surveying experience (Mr. Andy Teal and Dr. Ed Owens) to accompany the team on two cruises. Techniques were further calibrated with these observers and no significant discrepancies were noted.

It is important to note that the 1993 survey did not attempt to go to all sites that were likely to contain oil or even known to contain oil. The site-selection process relied on what was found in 1991 and 1992. These earlier surveys were biased toward cleanup considerations, and even if sites were known to have oil, they may not have been included on survey lists because it was thought not enough oil existed or environmental conditions made cleanup impractical. In developing the 1993 survey list, the ADEC augmented 1991 and 1992 survey data with other survey data and knowledge going back to the beginning of the spill. The decision to include a site for the 1993 survey did not consider earlier decisions based on cleanup criteria. The 1993 survey covered a large number and variety of oiled shoreline locations and included all locations with significant oil in 1991 and 1992. However, the 1993 survey is not a total measure of the remaining shoreline oil. Even though the survey did not measure all of the shoreline oil, trends in oiling derived from interannual comparisons of the sites that were visited may be extended to the entire spill area. This is possible because of the number and variety of the 1993 survey sites.

Field maps and notes from 1991, 1992, and 1993 were analyzed to yield estimates of the coverage of surface oil and the volume and distribution of oiled subsurface sediments. Comparisons of oiling were made between the years with regard to type of oil, physical setting (energy level), and past cleanup activities. Great care was taken to correlate the specific recorded locations between the years using the 1993 locations as the standard. Locations of surface and subsurface oiling, as noted on the field maps and forms in 1993, were traced back to 1992 and 1991.

Results

Results from this study show that in 1993 there were still locations in Prince William Sound with substantial surface and subsurface oil. Surface oil was discovered at all 45 ground survey sites and oil sheens were apparent at many sites. Surface oil locations were widely scattered, however, and only about 4.8 km of shoreline were found to be contaminated. This is a conservative estimate for the length of contaminated shoreline because not all of the shoreline was surveyed (see methods section above). Data from this study and reanalyzed data from the 1991 and 1992 surveys indicate that surface oil reduced by about one-half from 1991 to 1992, but that little reduction occurred from 1992 to 1993. We attribute most of the reduction that did occur to manual removal and raking in 1991 and 1992.

Surveyors measured 109 distinct locations with visually detectable subsurface oil that was typically in the form of lenses 3 to 15 cm thick underlying clean sediments. The areas of these locations ranged from four square meters to several thousand square meters with varying percentages of oil coverage. A total of 2,041 m^3 of oiled, subsurface sediment affecting a total of about 7 km of shoreline was discovered. These are conservative estimates of remaining subsurface oil because not all of the shoreline was surveyed (see methods section above). This study shows that subsurface oil decreased by at least one-half from 1991 to 1993, but that there appears to have been a significant slowing in the rate of reduction from 1992 to 1993. This slowing is because of less treatment occurring in 1992 than in 1991 and the natural entrenchment of remaining oil. There was also a consistent shift toward lower oil concentrations in sediments from 1991 to 1992 to 1993. In 1991, for the locations surveyed in this study, most of the heavy subsurface oil resided in high-energy locations. By 1992, however, most of the heavy subsurface oil was in moderate-energy locations, which continued to be the case in 1993. Considerably more reduction occurred at aggressively treated (tilled or excavated) than at nontreated locations.

Discussion

Surface oil that remained in 1991 has proven to be resilient. By 1991 most of the surface oil resided as asphalt, surface oil residue, and mousse between mid- to upper-intertidal large boulders along low-, moderate- and high-energy shorelines. Asphalt was also present on the upper intertidal surfaces of sheltered pebble and cobble beaches and bedrock. In 1993, oil persisted in these settings. It is important to note that even though a shoreline may have an overall high-energy setting, surface oil has survived in sheltered subenvironments formed by large boulders, bedrock outcrops, and bedrock fractures. Reduction since 1992 has been incremental and mostly related to treatment. There was probably little improvement in surface oil for several years after 1993.

Since 1991 there has been a shift in relative percents of the various subsurface oil concentration categories. This phenomenon supports the interpretation for a significant reduction. For sediments containing oil, there was a consistent shift toward lower oil concentrations from 1991 to 1992 to 1993. The large decrease in relative amounts of heavily-oiled sediments from 1991 to 1992 is probably mostly caused by targeted and aggressive treatment of heavily-oiled locations in 1991. In 1993, there was a more even distribution of oil concentrations than in earlier years because of the following: (1) the persistence in 1993 of heavily-oiled sediment that was not effectively treated and did not noticeably degrade in place; (2) the degradation of heavily- and moderately-oiled sediment to lightly-oiled sediment causing a relative increase in the amount of lightly-oiled sediment; and (3) the disappearance of very light oiling.

Among the sites surveyed for this study, most of the heavy subsurface oil resided in high-energy locations in 1991, but by 1992, most of this oil was in moderate-energy locations, which continued to be the case in 1993. This trend occurred despite the fact that in 1991 only 28% of heavily-oiled sediment in high-energy locations was mechanically tilled compared to 72% in moderate-energy locations The shift in oil setting illustrates that the heavy, recalcitrant oil is in moderate-energy locations where energy levels are high enough to prevent fine-grained sediments from decreasing permeability and thus preventing subsurface oil penetration, but not high-enough to cause significant sediment movement. For this reason, these locations have not responded to treatment or natural processes as well as other locations. These locations are typically along boulder-dominated limbs of pocket beaches and in bedrock- and boulder-sheltered areas along otherwise high-energy shorelines where large surface armor or local wave shadowing has prevented natural or unnatural physical removal.

Although we detected a significant amount of natural subsurface oil reduction, considerably more reduction occurred at treated than at nontreated locations. Tilling was more effective at high-energy locations than at moderate- and low-energy locations. After tilling, wave and tidal energy is required to actually release and disperse the oil and this is apparently much more effective in high-energy locations than in moderate-energy locations. Low-energy locations also responded to treatment better than moderate-energy locations. This is likely because of relying on oiled-sediment removal instead of tilling for treatment of low-energy locations.

With all the activity by government agencies, Exxon, and individuals, it is unlikely that large areas of concentrated oiling have escaped "official notice." For various reasons, however, some areas were not included in the 1993 survey. Set-aside sites, for example, were not included in the above analysis of ground surveys, and two other sites with oil on Smith and Seal Islands were not included. Even though we did not measure all of the remaining oil in Prince William Sound, we visited a sufficient number and variety of sites to state with confidence that we observed the dominant shoreline oiling characteristics and that our numbers for reduction apply to Prince William Sound as a whole. Our absolute numbers for remaining oil, however, are minimum values.

Studies of the *Arrow* and *Metula* oil spills indicate the residence time of shoreline oil in high-latitude marine environments. In 1970, the tanker *Arrow* spilled Bunker C fuel oil contaminating 305 km of shoreline in Chedabucto Bay, Nova Scotia, Canada. The oiled shorelines included low- to high-energy settings and consisted of rocky shoreline and beaches derived from glacial till. Responders cleaned only about 48 km of shoreline. In 1974, the supertanker *Metula* spilled 51,500 tons of light Arabian crude and 2,000 tons of Bunker C in the Strait of Magellan, Chile. The oil contaminated 65 to 80 km of shoreline and no cleanup occurred. Most of the oiled shoreline consisted of exposed mixed sand and gravel beaches. More than six years after these spills, surface oil remained on the shorelines. The *Arrow*-oiled shoreline showed much improvement, but *Metula* oil remained in large amounts. Much of the residual oil from these spills occurred in low-energy settings in the form of asphalt pavements and surface residues. These pavements physically stabilize sediment and hinder natural mechanical dispersal. They also have a weathered crust that hinders other degradation processes such as clay-oil flocculation and biodegradation.

In light of the persistence of shoreline oil from the *Arrow* and *Metula*, it is not surprising that oil remained from the *Exxon Valdez* in 1993, four years after the spill. Oil probably persisted for at least several years at many of the locations surveyed in 1993 and may exist today. The cleanup operations from 1989 through 1992 removed and helped prevent the formation of asphalted-sediment pavements, which greatly reduced the amount of oil remaining in 1993.

The deposition of subsurface oil in Prince William Sound appears to be more extensive and persistent than that reported for the *Arrow* and *Metula* spills. It is important to note the persistence of *Exxon Valdez* oil below surface armor along moderate- and high-energy shorelines. Subsurface (and surface) oil also persisted in wave shadows formed by large boulders, bedrock outcrops, and abrupt changes of shoreline orientation such as in pocket beaches. Oil persisted in these wave shadows which may occur along shorelines with overall high-wave energy. Tilling speeded the removal of subsurface oil, but large surface armor and obstructing wave shadows lessened the effectiveness of tilling or prevented tilling in many of the locations with subsurface oil in 1993.

Conclusions

1. The *Exxon Valdez* oil spill contaminated 782 km of shoreline in Prince William Sound, and more shoreline outside the Sound, during the spring and summer of 1989. By 1991, probably less than 10% of the originally oiled shoreline still contained surface oil with only 1.4 km being heavily oiled. Subsurface oil, however, remained along about 36.8 km of shoreline.

2. Surface oil was discovered at all the 45 ground survey sites visited in 1993 and sheening was apparent at many sites. The estimated area the oil would cover if it were amassed is from 2,964 to 10,230 m^2. The oil types include asphalt (AP), mousse (MS), surface-oil residue (SOR), cover (CV), and coat (CT). This oil was distributed in 217 locations along a total of

about 4.8 km of shoreline. AP, MS, and SOR alone affected about 3.7 km of shoreline and occurred at 171 locations. These are conservative estimates for the amount of contaminated shoreline in 1993 because not all of the shoreline was surveyed. The average oiled location with SOR, AP, or MS was 160 m^2 in size and had about a 23% oil coverage. AP and SOR occurred in about equal amounts and dominated the surface oiling in Prince William Sound.

3. Surface oil decreased by about one half from 1991 to 1993. Manual removal and raking in 1991 and 1992 caused most of the decrease.

4. In 1993, surveyors measured 109 distinct locations with visually detectable subsurface oil. A total of 2,041 m^3 of oiled, subsurface sediment, which affected 33,749 m^2 of shoreline, was discovered. The total length of affected shoreline was about 7 km. These are conservative estimates for the amount of contaminated shoreline in 1993 because not all of the shoreline was surveyed. Subsurface oil lenses were typically 3 to 15 cm thick and occurred 5 to 30 cm below clean sediments.

5. Subsurface oil decreased by at least one half from 1991 to 1993. The rate of reduction decreased from 1992-93 compared to 1991-92. This slowing is because of less treatment occurring in 1992 than in 1991 and the natural entrenchment of remaining oil.

6. Oil amount and distribution in 1993 were a function of natural protection from waves and surface water flow, sediment dynamics, and difficulty in performing cleanup. By 1992, most of the oil easily removed by natural and treatment means had disappeared. Reduction from 1992 to 1993 was incremental and mostly related to treatment, particularly for surface oil. The rate of oil reduction since 1993 probably continued to decreased for several more years.

7. Tilling and natural removal were more effective at high-energy locations than at moderate-energy locations. The reasons for the difference are a function of sediment transport dynamics.

8. Locations with recalcitrant subsurface oil were typically in moderate-energy subenvironments along otherwise high-energy shorelines. These locations occur along boulder-dominated limbs of pocket beaches and in bedrock- and boulder-sheltered areas. Large boulders and bedrock obstructions hindered physical treatment, and local wave shadowing at these locations prevented natural or treatment-related physical cleaning. The overall high-energy settings, however, prevents the deposition of fine-grained (mud) matrix sediments that would have decreased permeability and oil penetration to the subsurface, as is the case along low-energy shorelines. Moderate-energy shorelines with permeable gravel beachess also retained subsurface oil where sediment erosion had not reached the depth of the oil since the spill. Moderate- and High-energy locations with boulder and cobble surface armor retained oil in the sandy matrix below the surface layer.

9. Future spill response efforts need to consider the effects of local wave shadows and surface armor on the natural retention of oil and on the effectiveness of cleanup efforts. Extra protection of these local areas during a spill and more attention during a cleanup are required to prevent the formation of recalcitrant oil deposits.

10. Process studies of beach sediment dynamics are needed to understand the fate of shoreline oil and to aid in making cleanup decisions for future oil spills in Prince William Sound or similar areas. Much of the remaining subsurface oil resides in the sediment of moderate- and high-energy boulder, cobble, and pebble beaches that are adjusting to uplift caused by the 1964 earthquake. A lack of understanding of the sediment dynamics of these beaches contributed to a lack of appreciation of the continuing problem they would present in the *Exxon Valdez* oil spill.

Appendix A: Management, Policy, and Community Issues

Beach cleaning at this point - especially by manual means - would likely produce only incremental results. A handful of sites lend themselves to manual work, and the amount of work is probably low relative to the time, money, and effort required to conduct it. Agency representatives from the Alaska Department of Natural Resources and the U.S. Forest Service expressed some interest in limited remediation at some sites, but this did not appear from their comments to be a high priority. In Chenega, however, remediation remains a priority.

Three practical options for remediation as a restoration strategy are (1) remove debris left by cleanup crews and completed scientific surveys, (2) manual cleanup of selected, high-priority sites identified by Chenega Bay, and (3) manual remediation of mussel beds that remain oiled.

INTRODUCTION

The T/V Exxon *Valdez* ran aground on March 24, 1989 and spilled 11 million gallons (about 35,500 metric tons) of Alaska North Slope crude oil into Prince William Sound, Alaska (Harrison, 1991; Piper, 1993). By the end of September 1989, hundreds of kilometers of shoreline in Prince William Sound had been contaminated by varying amounts of oil (Figure 1). Since the first summer of the spill, response teams conducted annual surveys of the shorelines to map the distribution of visible oil in the intertidal and supratidal zones. Information from these surveys was used to make decisions on the type of treatment, if any, to be performed at particular sites. The surveys provide data on the amount and type of shoreline oil and the effects of cleanup and physical setting on the removal of oil. The 1993 shoreline survey described in this report continues the time series begun in 1989 and covers 45 sites in Prince William Sound (Figure 2) and 2 sites in Tonsina Bay on the Kenai Peninsula (Figure 1). Twelve detailed transect surveys were also remeasured in 1993 (Figure 2). In addition to summarizing shoreline oiling conditions in 1993, this study makes comparisons with the 1991, and 1992 surveys. The *Exxon Valdez* spill is also compared with the *Metula* and *Arrow* spills. A review of shoreline oiling and cleanup efforts in Prince William Sound places the findings in perspective.

Physical Setting of Prince William Sound

The geologic and tectonic setting of Prince William Sound has created a complicated shoreline and hence a difficult environment for oil spill response efforts. Tilted, folded, and faulted rocks of the Orca and Valdez Groups form the bedrock islands of the Sound (Nelson et al., 1985). The rocks in these Groups include interbedded shales and sandstones, and metasedimentary and volcanic rocks. Gravel pocket beaches and coves have formed where steeply dipping, less resistant sedimentary rock layers and faults are present. Pleistocene glaciers filled the Sound and scoured fjords and embayments that are now 800 m deep (Sharma, 1979). Nearshore gradients are steep with water depths typically more than 20 m just 100 m offshore (Short, et al., 1996). Forty percent of the initially oiled shoreline is either mixed sand and gravel or gravel beach, 30% is sheltered rocky coast, 23% is exposed rocky coast or wave-cut rock platform, and the remaining 7% include sand beaches, exposed and sheltered tidal flats, and marshes (Michel and Hayes, 1991).

Prince William Sound is on the southern boundary of the North American Plate. This active tectonic setting affects the morphology and sedimentology of the shorelines. The 1964 "Good Friday" earthquake caused a 1-m uplift of the shorelines in the western part of the Sound. Uplift increased toward the east to as much as 8 m on Montague Island, which borders the Sound on the east (Figure 2) (Plafker, 1969). This recent uplift is a major factor controlling the geomorphology and sedimentology of the beaches affected by the spill (Hayes and Michel, 1991). The earthquake raised broad and gently sloping wave-cut platforms into the intertidal zone, caused the creation of gravel beaches with profiles controlled by the underlying bedrock, and increased the supply of large, angular boulders to beaches with backing cliffs. Shoreline morphology and sedimentology are still adjusting to the uplift.

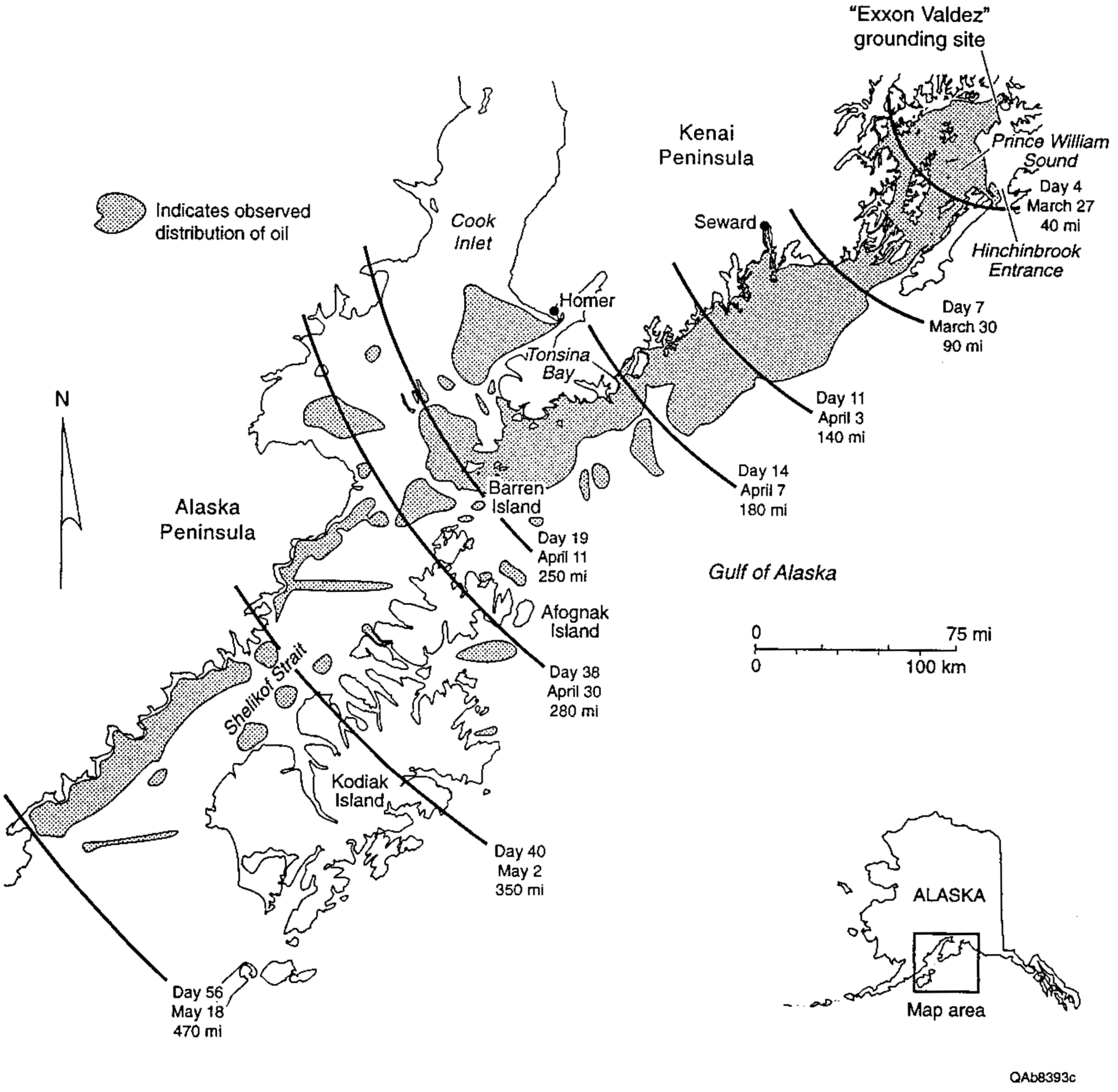


Figure 1. Composite overview of oil on water from March 24, 1989 to June 20, 1989. Data compiled and mapped by the Alaska Department of Environmental Conservation.

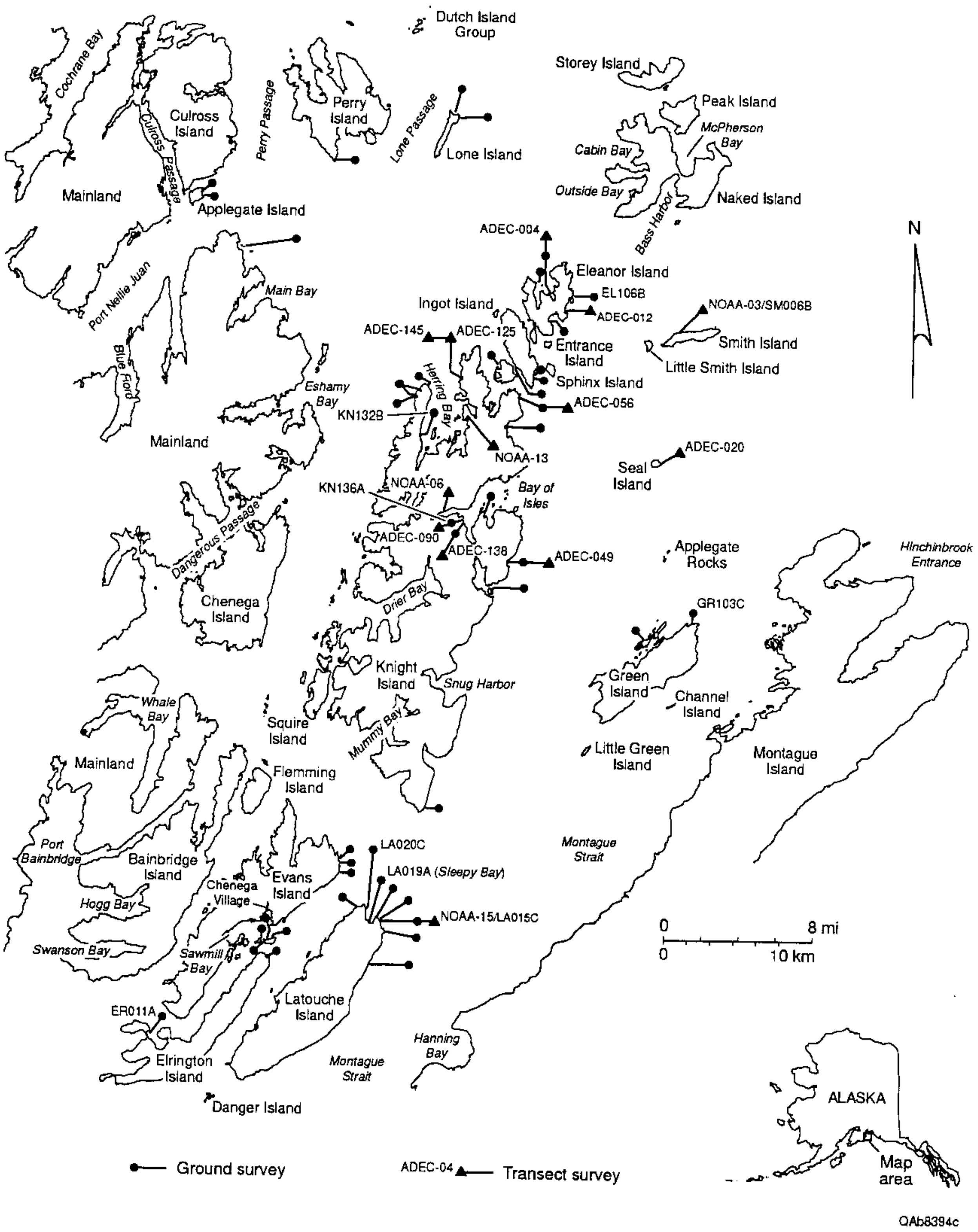


Figure 2. Locations of 1993 ground and transect survey sites in Prince William Sound.

The weather in the Gulf of Alaska and Prince William Sound is dominated by the west to east-northeast passage of cyclones along the Aleutian storm track (Wilson and Overland, 1986). During the winter months from October through April, an average of one storm every four or five days crosses the Gulf of Alaska (Hartmann, 1974). The coastal mountains block the passage of these storms causing them to linger and dissipate in the Gulf. These storms cause winds of up to 40 m/s. Storm winds in Prince William Sound are generally from the southeast, east, and northeast but the wind field is variable due to coastal wind jets, gap winds, katabatic winds, and topographic sheltering (Wilson and Overland, 1986; Michel and Hayes, 1991). Although the Sound commonly experiences high winds for several days during winter storms, the waves generated are limited by fetch. There are no quantitative wave records for the Sound, but beaches with well-rounded cobbles and boulders and storm berms built above the mean-high tide level attest to high wave energy (breaker heights of 2 m or more). These beaches occur along north-, east- and south-facing shorelines with fetches of 10 km or more. On the other hand, poorly sorted, angular sediments indicate low wave energy conditions along shorelines in bays with short fetches or with narrow or westerly exposures.

High tides that stranded oil in the upper intertidal zones of beaches were a significant factor affecting the persistence of shoreline oil. Tides are semidiurnal with a slight diurnal inequality. Tide range between mean higher high and mean lower low water is 3.8 m and 3.1 m between mean high and mean low water (National Ocean Service, 1984). Multiple berms that form during neap and spring tides are common on gravel beaches. Currents in Prince William Sound are dominated by the Alaska Coastal Current. A portion of this current enters Hinchinbrook Entrance (Figures 1 and 2) and flows southwestward through the Sound. Near surface current speeds in Montague Strait vary seasonally from less than 20 cm/s to more than 150 cm/s (Royer et al., 1990). There are no shoreline features in the spill area primarily formed by the Alaska Coastal Current or tidal currents, and the effect of these currents on shoreline sedimentology is probably small.

History of Shoreline Oil

By May 1, five weeks after the spill, approximately 41% of the 11 million gallons of spilled oil landed on the shores of Prince William Sound (Galt et al., 1991; Wolfe et al., 1994). When the oil came on shore during the summer of 1989 it was mostly described as surface oil, and much of the oiling was mapped from aircraft (Gundlach et al., 1991). The Alaska Department of Environmental Conservation (ADEC) produced a map from these aerial observations that showed the cumulative and maximum level of oiling of shorelines in Prince William Sound during the summer of 1989 (ADEC, 1990). This map showed that 149 km were heavily oiled (Heavy oiling is defined as a band of oil more than six meters wide or covering more than 50% of the intertidal zone.) and that 459 km had at least light oiling (defined as a band of oil between one meter and three meters wide or coverage of the intertidal area from one percent to ten percent). Shorelines with very light oiling (a band less than one meter wide or coverage less than one percent) were not mapped. Exxon-sponsored workers estimated that 782 km of Prince William Sound shoreline were oiled to some degree during 1989 and that 140 km had heavy oiling (Owens, 1991; Stoker et al., 1993).

Cleanup activities occurred only in summer, and when the 1989 cleanup season ended in mid September, ADEC conducted extensive ground surveys (ADEC Post Treatment Survey also known as the Fall 1989 Walkathon (ADEC, 1989)) throughout the oiled area of Prince William Sound. Based on data presented on ADEC's maximum impact map (ADEC, 1990) and the fall ground survey (Gundlach et al., 1991), areas of heavy surface oiling were reduced by 50% over the summer. By the time of the fall survey, 76 km of Prince William Sound shoreline remained heavily oiled and 581 km had some oil. The reduction over the summer is attributed to the cleanup effort, infiltration of oil into permeable and porous beach sediments, and natural degradation and dispersal. The cleanup effort included (1) massive cold- and hot-water flushing (Nauman, 1991), (2) manual removal, and (3) fertilizer application to enhance biodegradation (Nauman, 1991).

During March and April of 1990, State and Federal Agencies and Exxon jointly conducted ground surveys throughout the spill area during the Spring Shoreline Assessment Program (SSAP) (Exxon Corporation, 1990; Owens and Teal, 1990a). Gundlach and others (1991) compared the fall 1989 and spring 1990 surveys of Prince William Sound and found that the length of heavily oiled shoreline decreased by 73% from 76 km to 21 km and that the length of shoreline contaminated with any amount of visible oil decreased by 28% from 581 km to 420 km. In a similar comparison, Owens and Teal (1990b) found that the length of shoreline with heavy surface oil reduced by 78% and that the length of shoreline with any oil decreased by 40%.

ADEC, the National Oceanographic and Atmospheric Administration (NOAA), and Exxon also conducted their own detailed transect surveys before, during, and after the 1989/90 winter. These transect surveys measured the rate of removal of surface and subsurface oil along consistently oriented lines across the beach. Gundlach and others (1991) (ADEC surveys) reported that surface oil reduced by 81% during the 1989/90 winter and that the volume of subsurface oiled sediment reduced by 41% at 21 transect locations representing a variety of shoreline sediment types and degrees of exposure to wave energy . Jahns and others (1991) (Exxon surveys) analyzed 9 high-energy, 4 moderate-energy, and 3 low-energy sites from Prince William Sound where at each site they measured about 10 transects spaced about 10 m apart. They found that the amount of surface oil decreased by about 76% over the 1989/90 winter. Jahns and colleagues also estimated that at high-energy sites subsurface oil concentrations expressed as a percentage of sediment weight reduced from 0.8% to 0.1% for about an 88% oil weight reduction. Subsurface oil at their low- and moderate-energy sites reduced from 0.05% to 0.01% for about an 80% reduction. During the 1989/90 winter, Michel and others (1991) and Michel and Hayes (1991) (NOAA surveys) measured an 80% reduction of surface oil coverage at exposed beaches, 60% at intermittently-exposed beaches, and 50% at sheltered beaches. They also reported that subsurface oil in exposed cobble/boulder beaches was removed from the upper 20 cm by wave action, and that oil below the active sediment layers decreased an average of 40% by weight. In more sheltered areas, Michel and colleagues found that little subsurface oil reduction occurred in contrast to the study by Jahns et al. (1991).

Reduction of shoreline oil over the first winter is attributed to mobilization and dispersal into the Sound by wave action, tides, freshwater runoff, and clay-oil flocculation. Clay-oil flocculation (Jahns et al., 1991; Owens et al., 1994; Bragg and Yang, 1995) occurs where micron-sized mineral grains interact with shoreline oil effectively lifting the oil off surfaces and dispersing it into the open water in the form of fine-grained clay-oil aggregates. This process may explain why surface oil significantly decreased even in areas of low-wave energy and no beach erosion during the 1989/90 winter (Jahns et al., 1991; Owens et al., 1994; Bragg and Yang, 1995).

Exxon conducted a second season of intensive cleanup during the summer of 1990. Cleanup methods included (1) removal of oiled sediment, mousse, and tarmats, (2) mechanical tilling of sediment to facilitate wave washing, (3) relocation of sediment in upper intertidal and supratidal berms to the mid-intertidal for washing and redistribution by wave action (berm relocation), (3) spot washing of inaccessible sediment, and (4) fertilizer application to enhance biodegradation (Nauman, 1991). No spill-wide survey was conducted at the end of the 1990 cleanup season, but Exxon, NOAA, and ADEC continued to monitor their earlier established transect locations during the 1990 summer and fall and during the 1990/91 winter and early spring.

In the spring of 1991, workers conducted a second interagency, spill-wide ground survey called the May Shoreline Assessment Program (MAYSAP) (Exxon Corporation, 1991). During this survey, ADEC personnel on the survey teams made a special effort to map the distribution of intertidal and supratidal subsurface oil. ADEC produced a map in the spring of 1991 that depicted the distribution of subsurface oil in Prince William Sound and estimated that 24.6 km of shoreline contained relatively heavy subsurface oil and another 12.2 km contained relatively light subsurface oil (ADEC, 1991). Stoker and others (1993) estimated that by May of 1991, 97 km of Prince William Sound shoreline had some form of oil and 1.4 km had heavy oiling. Using their numbers for 1989 this would constitute an 88% reduction for all levels of oiling and a 99% reduction for heavy oiling over the two-year period. Transect surveys by NOAA (Michel and Hayes, 1993a,b) and ADEC (Pavia et al., 1991) confirmed that very little surface oil remained, and that the problem areas mostly involved subsurface oil in low-energy mixed sand and gravel beaches and subsurface oil in high-energy gravel beaches with surface armors of cobbles and boulders and protective bedrock outcrops. Exxon conducted a third extensive cleanup season during the summer of 1991 using the same techniques as in 1990.

An abbreviated Exxon and interagency shoreline survey was conducted during the spring of 1992 (Final Shoreline Assessment Program, FINSAP (Exxon Corporation, 1992)) during which surveyors performed minimal manual cleanup. Stoker and others (1993) state that by June 1992 some form of oil remained on 10.3 km of Prince William Sound shoreline and that only 0.16 km had heavy oiling. Stoker and colleagues' data indicate a reduction of 89% for all oiling levels and heavy oiling alone from 1991 to 1992, but it is not clear if they included subsurface oil in their estimates. NOAA reoccupied their transects in August 1992, and based on those data, Michel and Hayes (1993b) stated that by 1991 very little surface oil remained but that there was little change between 1991 to 1992, particularly in sheltered environments. Michel and Hayes' observations also included the following: (1) berm relocation was very effective in removing subsurface oil stranded in upper intertidal berms and storm berms, (2) subsurface oil remained beneath the armored surfaces of high-energy boulder and cobble beaches and on sheltered rubble shores, (3) the upper 25 cm of sediment was clean on gravel beaches where oil had deeply penetrated, (4) on sheltered rocky shores, oil was persistent and formed pavements on sites not treated, and (5) films of oil on water (sheening) remained a problem where subsurface sediments were moderately contaminated.

Absolute amounts of oiling differ in the above cited studies; however, during the first summer after the spill, surface oiling decreased by about 50% and significant subsurface oil remained at the end of the first cleanup season. During the first winter, surface oil decreased by 50% to 80%; sheltered locations showed the least change because of the lack of wave energy. Subsurface oil also decreased over the first winter showing a reduction of about 40% to 88%, but with little reduction in sheltered settings. By spring 1990, the greatest and most difficult problem was subsurface contamination that caused oil sheens on water, and the cleanup operation addressed this with mechanical tilling, berm relocation, and oiled sediment removal. During the 1990 cleanup and the winter of 1990/91, surface oiling decreased, but the amount is harder to estimate. By the spring of 1991, probably less than 10% of the oiled shorelines still contained visible surface oil. The remaining surface oil was present in scattered locations between surface boulders and bedrock and in bedrock fractures. Surface asphalt in sheltered locations also remained. Despite the successes of mechanical tilling and berm relocation during the 1990 cleanup season, subsurface oil remained in 1991 in some high-energy gravel and low-energy rubble shorelines. This subsurface oil was a concern, and Exxon addressed it late in the 1991 cleanup season with mechanical tilling and berm relocation where sedimentological and ecological conditions allowed.

The results of the 1993 survey presented herein shows that a large reduction in surface and subsurface oil occurred from 1991 to 1993. The rate of reduction was lower in 1992 particularly for surface oil. Major cleanup operations ended in 1991. Only manual raking of sediment over small areas took place in 1992, and no cleanup occurred in 1993. By 1992, oil remained only in those locations naturally protected from waves, tidal action, and freshwater runoff and where effective cleanup had been inhibited by the physical or ecological setting.

OBJECTIVES

The overall goal of the 1993 shoreline survey was to determine if shorelines in Prince William Sound and on the Kenai Peninsula had recovered sufficiently to facilitate normal shoreline activities. Specific objectives included the following: (1) survey selected shorelines for oiling; (2) determine if resource uses are affected by oiling or spill-related activities; (3) Perform light-duty manual treatment to improve resource uses; (4) write work orders for local crews to perform additional cleanup, if necessary; and (5) assess changes in oiling over time, as possible.

METHODS

Ground Surveys

The 1993 survey used the same techniques (Exxon Corporation, 1991) as the 1990, 1991, and 1992 surveys cited previously. Surveyors dug pits in the beaches and turned over cobbles and boulders to reveal hidden oil where earlier surveys had recorded the presence of oil. Surveyors also dug pits in other areas where there was a possibility of oil based on the sedimentological setting. They then recorded the oil distribution on field maps and forms and classified surface and subsurface oil as described below. The sizes of locations with oil were estimated by pacing or measuring with a tape, and visual estimates were made of the percent oil cover within the area. Workers recorded the depth and thickness of subsurface oil revealed in the pits and described sediment texture. Surveys occurred within two hours of low tide and always when the tide level was lower than two meters above mean low water.

Field classification of oil type and percent cover are consistent with previous surveys (Exxon Corporation, 1991) and are presented in Table 1. These classifications were designed for the consistent collection of qualitative field data. The categories are broad and reflect the problems associated with making observations in areas where oil cover and coastline morphology vary greatly. These general classifications are now in wide use (Owens and Taylor, 1993).

Survey team members worked together to calibrate their judgments on oiling types and percent coverage estimates. All survey work was done as a team with constant interaction between surveyors. All surveyors for the 1993 survey were experienced and had worked on the spill since 1989. In addition, Exxon assigned two observers with extensive shoreline surveying experience (Mr. Andy Teal and Dr. Ed Owens) to accompany the team on two cruises. Techniques were further calibrated with these observers and no significant discrepancies were noted. Owens (1984) compared independent observations of two surveyors and estimated the repeatability of percent oil coverage estimates to be ± 5% for a mixed sand and gravel beach.

Michel and Hayes (1994 p. 2-4) compared the visual subsurface oil classifications used in this study with quantitative total petroleum hydrocarbon (TPH) measurements (Table 1). Medium oil residue (MOR) classifications corresponded to sediment with 800 to 4,700 milligrams of TPH per kilogram of sediment. The reason for the variation is primarily the wide range of sediment size and sorting causing variance in the TPH by sediment weight measures (i.e. finer sediment texture results in higher TPH by weight measures). The sample size required to achieve repeatable TPH measurements within a single location would be very large and impractical in gravel beaches. TPH comparisons between beaches of different sediment size and sorting is misleading. This study, therefore, compares visual categories of oiling concentrations and does not attempt to assign TPH by sediment weight values to these categories. Photographs illustrating the classification appear in Gibeaut et al. (1994).

The decisions to include sites in the 1990, 1991, and 1992 surveys were based primarily on the most recent information about the amount of oil remaining on the coastline. An interagency group, which included Exxon, compared data and negotiated the final survey lists. The primary criteria for selecting a site for survey was whether the last recorded oiling data suggested that more cleanup might be needed. Some sites that may contain oil in 1993, therefore, may have been dropped from earlier year's survey lists because of a lack of willingness to treat a site by the government agencies and Exxon. In developing the 1993 survey list, the ADEC augmented 1991 and 1992 survey data with survey data and knowledge going back to the beginning of the spill. The decision to include a site did not consider earlier decisions based on cleanup criteria. Instead, ADEC workers listed for the 1993 survey those sites that had at least one of the following characteristics:

Table 1: Field Oiling Classifications

Surface Oil Types	Abbreviation	Definition
asphalt pavement	AP	Heavily oiled beach sediments held cohesively together.
Mousse/pooled oil	MS	Any oil/water emulsion with a thickness of more than 1 cm.
tar balls, patties, tar patties	TB	Small, distinct oil deposits lying on top of the beach surface; possibly binding debris but typically not sediments
surface oil residue	SOR	Significantly oil coated beach sediments in the top 5 cm; sediments do not form a cohesive layer; may be described as heavy or light.
Cover	CV	Oil more than 1 mm to 1 cm thick.
Coat	CT	Oil more than 0.1 mm to less than or equal to 1 mm thick; can be easily scratched off with fingernail.
Stain	ST	Oil less than or equal to 0.1 mm thick; cannot be easily scratched off with fingernail.
Film or sheen	FL	Transparent or translucent film or sheen.
Oiled debris	DB	Any oiled debris or cleanup material stranded on a shore.

Surface Oil Distribution Classes	Abbreviation	Definition
continuous	C	Area or band with 91% to 100% oil coverage.
Broken	B	Area or band with 51% to 90% coverage.
Patchy	P	Area or band with 11% to 50% coverage.
Splash	S	Area or band with 1% to 10% coverage.
Trace	T	Area or band with less than 1% coverage.

Subsurface Oil Types	Abbreviation	Definition	Concentration (from Michel and Hayes (1994) mg oil per kg sediment)	Weighting Value
oil pore	OP	Pore spaces are completely filled with oil resulting in oil oozing out of sediments - water cannot penetrate OP zone.		5
heavy oil residue	HOR	Pore spaces partially filled with oil residue but not generally flowing out of sediments.	7,700 - 17,900	4
medium oil residue	MOR	Heavily coated sediments; pore spaces are not filled with oil - pore spaces may be filled with water.	800 - 4,700	3
light oil residue	LOR	Sediments lightly coated with oil.	470 - 3,300	2
oil film	OF	Continuous layer of sheen or film on sediments - water may bead on sediments.	80 - 1,000	1
trace	TR	Discontinuous film; spots of oil on sediments; an odor or tackiness with no visible evidence of oil.		0.1

1) Continued surface or subsurface oiling over a significant portion of the shoreline segment.

2) Areas of moderate to heavy oiling (SOR, AP, MS, LOR, MOR, HOR, OP)

3) Areas in which several years of oiling data suggested that oil might remobilize and create new visible oiling in a subsequent year, regardless of the previous year's cleanup efforts.

4) Areas of emerging concern such as the heavily oiled mussel beds which had received little or no cleanup over time.

5) Areas of specific and consistent concern on the part of an agency, landowner, or nearby community.

The 45 sites and 12 transect locations in the 1993 survey covered a large number and variety of oiled shoreline locations and included all locations with significant oil in 1991 and 1992 (Figure 2).

Transect Surveys

Repeated transect surveys provide quantitative data on the geomorphology of the beach including erosional and depositional changes and how those changes relate to oiling. This type of survey entails measuring the relative height (profile) along a line oriented perpendicular to the shoreline trend (transect) and visually estimating sedimentological and oiling conditions along that line. Transect surveys only cover limited areas on select beaches. Thus there is a trade-off between the detail obtained with transect surveys and the ability to cover larger areas and many sites with the ground surveys. The 1993 survey used both techniques to at least partially avoid making that trade-off.

Transect locations in Prince William Sound have been established by various workers including those from ADEC, Exxon, and NOAA. These earlier workers chose transect locations to be representative of Prince William Sound, but the highly variable physical settings and cleanup activities made this task difficult. It was thought that the 1993 transects did not sufficiently cover enough locations with remaining oil to be representative of the entire Sound, nor did they necessarily cover specific areas of concern. Therefore, transect surveys in the 1993 study are used only to help evaluate observations made by the ground surveys. Nine of these sites were previously designated by ADEC for long-term monitoring (Pavia et al., 1991) and four were established by NOAA in 1989 (Michel et al., 1991; Michel and Hayes, 1991; Michel and Hayes, 1993a and b; Michel and Hayes, 1994).

Data Analysis

Field maps and notes from 1991, 1992, and 1993 were analyzed to yield estimates of the coverage and distribution of surface and subsurface oil. Comparisons were made between years with regard to amount and type of oil, physical setting (energy level), and past cleanup activities. During the years of cleanup operations, a hierarchy of shoreline designations was developed. A shoreline "segment" is the broadest designation and may include a piece of shoreline several kilometers in length. Depending on the history of the cleanup and oiling a "segment" may be divided into "subsegments". More specific locations within a subsegment are generally referred to as "beaches" or "sites". Beaches and sites within a subsegment are usually separated by geomorphic boundaries such as headlands or by stretches of shoreline that do not contain oil or were not surveyed. Contiguous areas of oiling within beaches and sites are here referred to as "locations". "Locations" have a consistent sediment type, energy setting, and cleanup history, and are the spatial level at which the subsequent analyses were performed. The specific areas surveyed at particular sites may affect the amount of recorded oil for a particular year. For this reason, estimates of trends in the amount of oil from year to year were determined using only those locations that covered the same place on the shoreline for each year.

Locations of surface oiling, as noted on the field maps and forms in 1993, were traced back to 1992 and 1991. The amount of surface oil cover was estimated by multiplying the area of each location by the percentage value of the lower and upper bounds of the field categories for surface oil coverage (Table 1). This yields a range for the Equivalent Area of 100% Oil Cover (EA) (Owens et al., 1994). The surface oil categories of tarballs (TB), stain (ST), and film (FL) (Table 1) are not tabulated for this study because they are relatively difficult to detect. For interannual comparisons, this study analyzed only the surface oil categories of asphalt (AP), mousse (MS), and surface oil residue (SOR). The wide range in EA is caused by a wide range in the field categories. This precludes the use of EA for interannual comparisons. However, the number of locations with oil and the area of shoreline affected with oil are tabulated for each year (Table 3).

Subsurface oiling locations were correlated between years using the 1993 locations as the standard. Horizontal distribution of subsurface oil was either estimated in the field or determined from field maps. Pits were dug to delineate subsurface oiling areas. Surveyors plotted the pits on field maps, which had a scale or features from which a scale could be calculated.

Subsurface oil was not always homogeneous within a location. In some cases, it was evident that subsurface oil was related to surface oil and did not occur where there was no surface oil. For these locations, subsurface oil cover and volume were estimated from the area of surface oil. Areas were often enclosed around pits with varying types of oil and some pits with no oil. In these cases, the coverage of particular types of oil or no oil were estimated by dividing the number of pits with similar conditions by the total number of pits dug in the area. This fraction was then multiplied by the total area of the location. The average oiling thickness was calculated for each type of oil found in a location and this number was then multiplied by the area measurement of that type to yield an oiled-sediment volume. An assumption of a 2 m by 2 m area surrounding isolated oily pits where no evidence of subsurface oiling existed between neighboring pits was used.

For each location, the oiled-sediment volume of each oiling category was multiplied by a "weight" corresponding to the relative concentration of the oil. The Weighted oiled-sediment volume (***WOSV***) is a way to track the relative amounts of oil. *WOSV* is defined as follows:

$$WOSV = 5V_{OP} + 4V_{HOR} + 3V_{MOR} + 2V_{LOR}$$

where V_{OP} is the volume of oil pore (OP) sediment in a location; V_{HOR} is the volume of heavy oil residue (HOR) sediment in a location and so on for the other oiling types (Table 1). For this analysis, the lightest categories, namely oil film (OF) and trace (Tr), were not used. *WOSV* for transect surveys are reported as volume per unit length of the transect. Other comparisons were made using just the heaviest oiling categories (OP and HOR), for which weighting was not performed.

Each location was classified by wave energy as either high, moderate, or low energy. Relative energy classification is determined by the fetch, shoreline orientation, biological character, and sedimentological characteristics such as sediment rounding and the presence or absence of storm berms. Energy level was assigned for subsurface oil on the "location" level, and in some areas varying energy levels may have been assigned to locations in the same sites depending on local wave shadow effects. For example, large boulders or bedrock outcrops may protect a location from wave action.

Cleanup information was examined at each location for comparison to oiling conditions. Sources for treatment activity in 1991 included the Federal On-Scene Coordinator work orders, ADEC Daily Shoreline Assessments that were completed by the State monitor for each day treatment occurred at a site, and supplementary State, Federal, and Exxon surveys and memos describing treatments. In 1992, treatments generally occurred in conjunction with the spring survey (Final Shoreline Assessment Program, FINSAP). Therefore, comments made on the FINSAP survey forms and the accompanying Daily Shoreline Assessment forms were analyzed. The State also did some surveying and cleanup independent of the joint FINSAP and these data were also considered. Cleanup activities were classified as either removal of oiled sediment, water washing, manual raking of surface oil, manual or mechanical (back hoe) tilling of subsurface oil, and relocation of oiled sediments from the high intertidal zone to lower on the beach. Raking, tilling and relocation were designed to enhance wave and tidal action in the release and dispersal of oil. No attempt was made to determine cleanup activities prior to 1991.

RESULTS

Surface Oil

Table 2 presents data for all surface oil recorded in 1993. Surface oil was discovered at all the 45 ground survey sites visited in 1993 and oil sheen was observed at many sites. An EA between 2,964 and 10,230 m^2 of asphalt (AP), mousse (MS), surface-oil residue (SOR), cover (CV), and coat (CT) was present. This oil was distributed over 217 locations along about 4.8 km of shoreline. AP, MS, and SOR alone affected about 3.7 km of shoreline and occurred at 171 locations for a total EA between 2,633 to 8671 m^2 (Table 2). Multiple oil types often combined to comprise the percent oil coverage of a location. Therefore, some locations given in Table 2 are counted more than once in the "# of Locations" row. The average size of an oiled location with SOR, AP, or MS was 160 m^2, and the average oil cover was about 23%.

AP and SOR occurred in about equal amounts and dominated the surface oiling characteristics for Prince William Sound in 1993. MS was a relatively minor component overall and was found in relatively small areas. One location in Sleepy Bay on Latouche Island (LA 019

A, Figure 2) contributed almost half the MS found. Here MS was trapped among boulders and cobbles in the mid-intertidal zone and escaped natural degradation and cleanup. CV and CT were also minor components compared to AP and SOR. CV and CT occurred as degraded "bathtub" rings at the high-tide level on bedrock and boulders and in very minor amounts in the surface cracks of cobbles and boulders.

Table 2: 1993 Surface Oiling (m^2 and m)

	Asphalt (AP)	*Mousse (MS)*	*Oil Residue (SOR)*	*Cover (CV)*	*Coat (CT)*	***Totals***
# of locations	110	25	132	37	119	
Equivalent Area (EA)	1,316 - 4,497	85 - 324	1,232 - 3,850	89 - 269	242 - 1,290	2,964 - 10,230
# of locations with AP, MS, SOR, CV, or CT						217
# of locations with AP, MS, or SOR						171
Equivalent area of AP, MS, and SOR						2,633 - 8,671
Length of shoreline with AP, MS, SOR, CV, or CT						4,840
Length of shoreline with AP, MS, or SOR						3,717
Area affected with AP, MS, SOR, CV, or CT						31,445
Area affected with AP, MS, or SOR						27,353
Average size of oiled location with AP, MS, SOR, CV, or CT						145
Average size of oiled location with AP, MS, or SOR						160
Average percent oil cover of locations with AP, MS, or SOR						23

Figure 3 is a plot of the percent oil cover and the EA of AP, MS, and SOR for each location. This plot illustrates the great variety in the size and percent oil cover of surface oil locations. Most locations plot in the middle and lower left with relatively small amounts of oil with sparse coverage. Locations in the upper right part of this plot have relatively large amounts of oil with dense coverage. These sites include areas where surface oil has been trapped and protected by large boulders even along high-energy shorelines such as the north shore of Latouche Island at LA015C (Figure 2). Figure 4b shows a typical area of MS, SOR, and associated subsurface oil among and beneath surface boulders at KN300A on Knight Island, a moderate-energy location. Large areas with high percent coverage of AP also occur on sheltered shorelines, such as along the shore of the high-tide lagoon at KN136A in the Bay of Isles (Figures 2 and 4c). The location with the greatest amount of oil at a high percent cover is on the north shore of Green Island (GR103C) (Figure 2). Here AP and SOR has been trapped in the fractures of vertically dipping shale bedrock on a raised wave-cut platform. The oil is in the upper intertidal zone which has further hindered natural removal. Not only have the bedrock fractures and large surface boulders naturally protected oil, they also have hindered effective cleanup.

Table 3 presents an interannual comparison of locations containing AP, MS, and SOR. This comparison is only for those locations that were surveyed each year since 1991. The parameters are the area of beach affected with oil and the number of oiled locations. As mentioned previously, the range in field oiling classification for percent oil coverage precludes the use of EA for interannual comparisons. In 1991, 173 locations were found with oil, but by

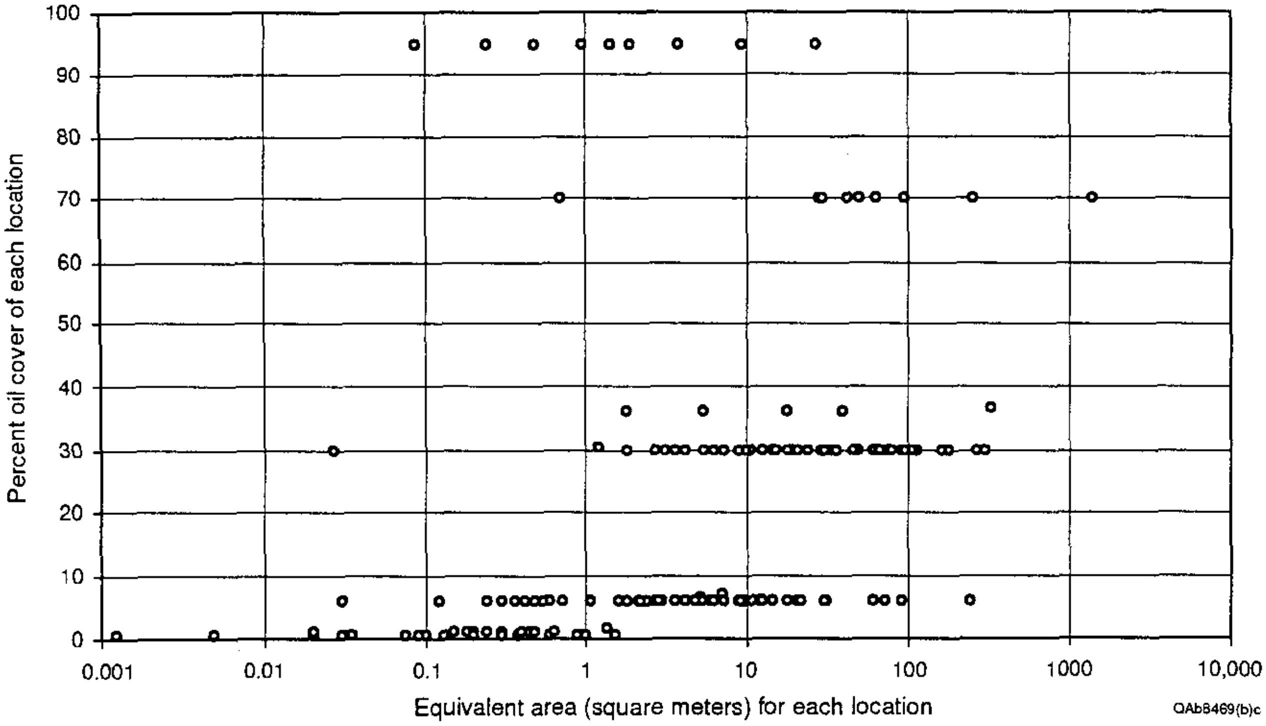
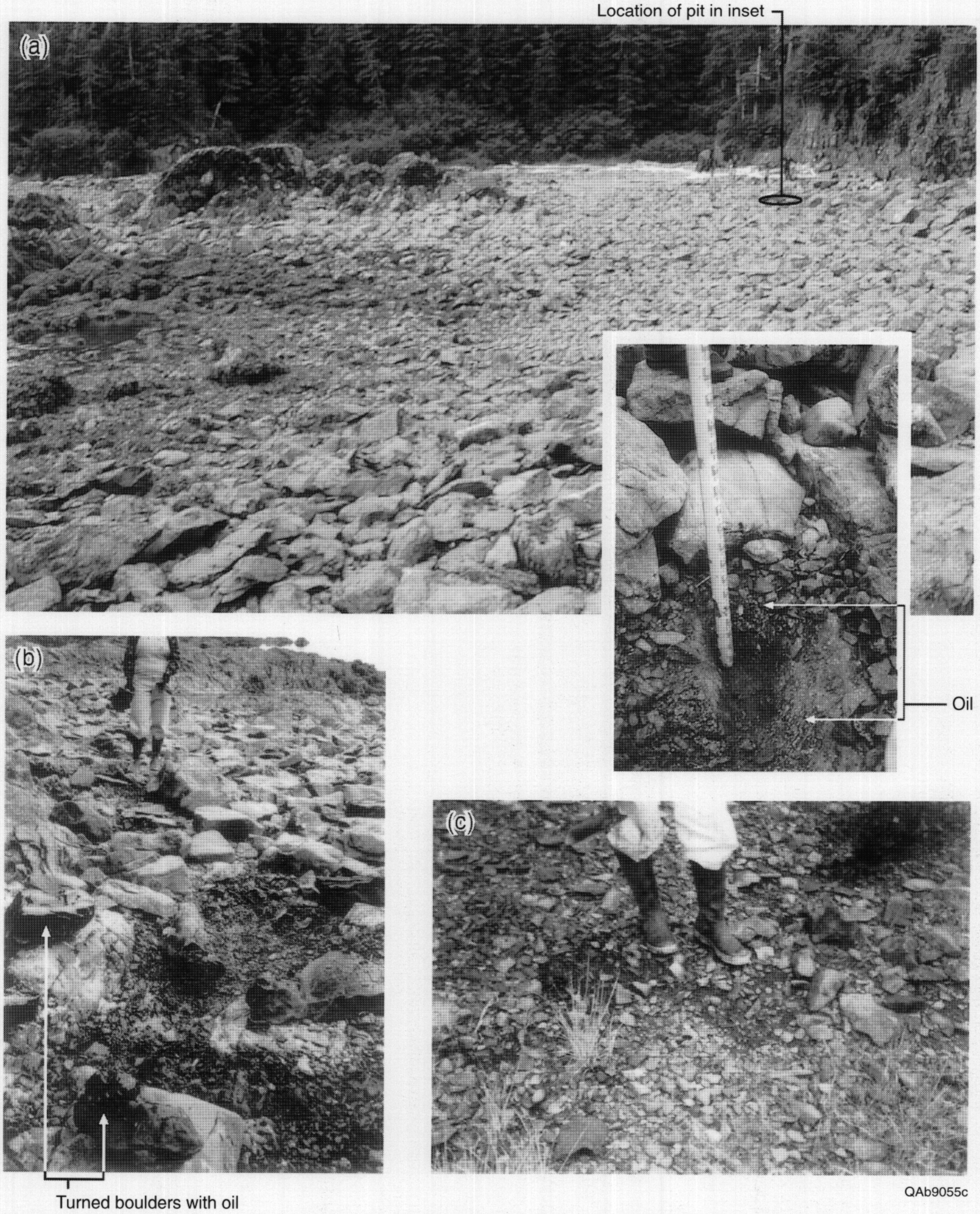


Figure 3. Percent oil cover versus the equivalent area (EA) amount of AP, MS, and SOR for locations measured in 1993. The horizontal axis is a logarithmic scale. Locations with large amounts of surface oil and a high percent coverage plot in the upper right.

Figure 4 (next page). Examples of shoreline oiling in Prince William Sound in summer, 1993. Shoreline locations shown in Figure 2. A) High-energy transect site ADEC-49 in Rua Cove. Lower intertidal zone shown in lower left portion of photo. OP and HOR trapped below surface boulders shown in inset. Rod is marked in 2 cm increments. Boulders and bedrock outcrops visible on left side of photo partially shield site shown in inset from wave attack. Figure 8 is a sketch of pit shown in inset. B) SOR, MS, and associated subsurface oil between and beneath upper intertidal surface boulders at KN300A on Knight Island, a low- to moderate-energy location. Ocean is visible in background. C) AP mixed with sediment (asphalted-pavement) on low-energy, pebble beach on KN136A in Bay of Isles, Knight Island. Person is standing on AP.


Location of pit in inset
(a)
Oil
(b)
Turned boulders with oil
(c)
QAb9055c

1992 only 124 of those same locations contained oil and in 1993 only 118 had oil (Table 3). In addition, the total oiled area and the average size of oiled locations decreased greatly from 1991 to 1992. There was, however, a relatively small increase in these parameters from 1992 to 1993. The average percent oil coverage for locations with oil remained nearly constant each year.

Table 3: Surface Oiling Change for Commonly Measured Locations (m^2 and %). Only AP, MS, and SOR Considered.

				Percent Change		
	1991	*1992*	*1993*	*'91 to '92*	*'92 to '93*	*'91 to '93*
# of locations with oil	173	124	118	-28	-5	-32
Average percent oil cover	20	21	21	5	0	5
Average area of oiled location	338	121	174	-64	44	-49
Total area of oiled locations	58,544	15,009	20,558	-74	37	-65

Subsurface Oil

In 1993, surveyors measured 109 distinct locations with visually detectable subsurface oil. The areas of these locations ranged from four square meters to several thousand square meters with varying percentages of oil coverage. A total of 2,041 m^3 of oiled subsurface sediment was discovered. Subsurface oil lenses were typically 3 to 15 cm thick and occurred 5 to 30 cm beneath clean sediments. The heaviest type of subsurface oil, oil pore (OP) and heavy-oil residue (HOR), occurred in 69 locations with a total oiled-sediment volume of 738 m^3. The total area of beach affected with subsurface oil was 33,749 m^2, and the total length of affected shoreline was about 7 km.

Table 4 presents interannual subsurface oiling comparisons using locations that were surveyed each year. The amount of subsurface oil decreased by about 90% from 1991 to 1993. The rate of decrease was lower for the period 1992 to 1993 compared to the 1991 to 1992 period. The WOSV and OP/HOR volumes show similar trends (Table 4). These reduction values include the effects of treatment in 1991 and 1992. The average subsurface oil lens thickness decreased from 11 cm to 9 cm from 1991 to 1993.

Natural subsurface oil reduction is estimated by only considering the locations where no subsurface treatment occurred in 1991 or 1992. WOSV for locations not treated decreased by 64%, and treated locations decreased by 86% (Table 4). For OP and HOR volumes, locations not treated decreased by 68%, and treated locations decreased by 89% (Table 4).

From 1991 to 1993, a shift occurred in the relative percentages of oiling types (Figure 5). OP and HOR dominated subsurface oiling in 1991 along with a large amount of OF and TR. In 1992, the dominant oiling types shifted to HOR, MOR, and OF/TR, and by 1993, there was a much more even distribution of oiling levels. There was also a shift in the distribution of oil according to energy level for the locations at the 1993 survey sites (Figure 6). In 1991, most of the OP/HOR subsurface oil was in high-energy settings and the least in low-energy settings, but by 1993, a relative decrease of oil at high-energy locations had occurred (Figure 6). In 1992 and still in 1993, moderate-energy locations contained most of the heavy subsurface oil at the sites surveyed (Figure 6).

TABLE 4: Subsurface Oil Comparisons for Commonly Measured Locations (m^3 and %)

	# locations	1991	1992	1993	*Percent change* '91 to '92	'92 to '93	'91 to '93
Summary							
WOSV	51	5,971	1,116	696	-81	-38	-88
# Locations with LOR to OP		45	27	13	-40	-52	-71
OP/HOR Volume	30	1,053	188	99	-82	-47	-91
# Locations with OP/HOR		30	15	11	-50	-27	-63
Treated							
WOSV	35	9,829		1,335			-86
OP/HOR Volume	29	1,745		194			-89
Not treated							
WOSV	39	1,797		648			-64
OP/HOR Volume	24	295		95			-68

Transect Stations: High-Energy, Boulder and Cobble Beaches

Five high-energy, boulder and cobble beaches with northeast to southeast exposures were studied. These sites are on the north shore of Smith Island (NOAA-003), the east shore of Eleanor Island (ADEC-012), the northeast shore of Knight Island (ADEC-056), the east shore of Knight Island (ADEC-049), and the north shore of Latouche Island (NOAA-015) (Figure 2). Surface oil along these transects was only minor in 1991 and 1992 and mostly related to relocated or tilled sediment. No surface oil remained in 1993 but subsurface oil remained in specific locations either on the transect or adjacent to the transect in relatively sheltered locations.

Transect stations ADEC-056 and ADEC-049 (Figure 7c,d) showed significant reductions from OP and HOR in 1991 to almost no oil in 1993. At station ADEC-049 in Rua Cove, OP and HOR oil remained in the upper intertidal (Figure 7d). This heavy oil was below two to three layers of subrounded surface boulders about 50 cm in size (Figures 4a and 8). Just below the surface layer was a 4 cm thick layer of subangular large pebbles. This pebble layer overlies large boulders with a sandy matrix. The oil resided in the lower half of the pebble layer and in the underlying sandy matrix from 32 cm to more than 52 cm below the surface. HOR oil also remained off the ADEC-56 transect among a group of large boulders (>100 cm) in the mid to upper intertidal zone. These boulders provided a local wave shadow that protected the oil from removal along this high-energy beach. ADEC-056 was treated in 1991 with tilling but not in the boulder-protected area. ADEC-049 was not treated in 1991 or 1992.

NOAA-003 on the north shore of Smith Island (Figure 2) showed no improvement since 1991 or 1992 and retained MOR to HOR across the mid to upper intertidal zone (Figure 7a). This beach showed net vertical accretion of 10 to 30 cm from 1992 to 1993. In 1993, subsurface oil was 10 to 25 cm below the surface and was present as deep as 43 cm. In the oiled area, the stratigraphy was similar to ADEC-49. Two to three layers of rounded surface boulders and cobbles overlayed a 5 cm pebble layer. Below the pebble layer, there was a boulder and cobble

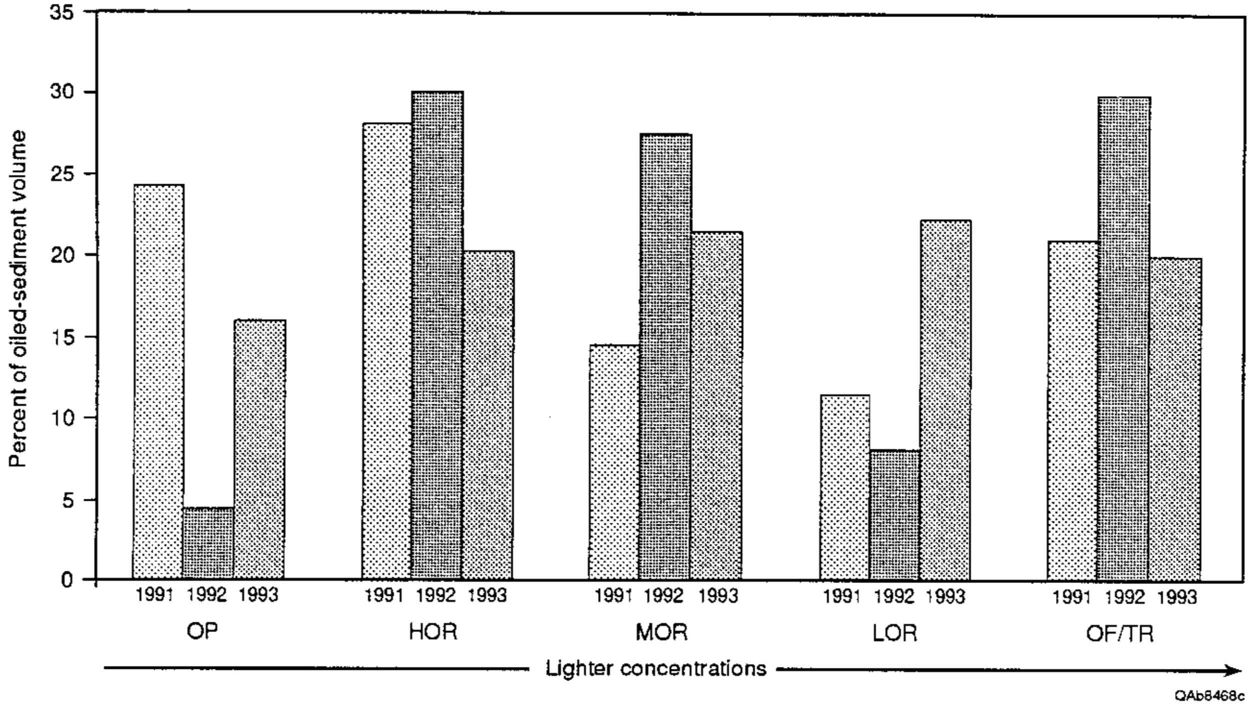


Figure 5. Relative percents of oiled-sediment volumes for each oiling level and for 1991, 1992, and 1993. All locations for each year were used in the calculations.

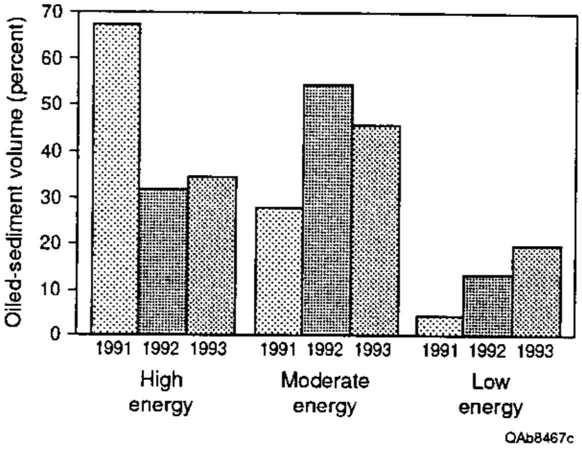


Figure 6. Relative percents of OP/HOR oiled-sediment volumes occurring in high- moderate-, and low-energy settings. Distributions are given for 1991, 1992, and 1993. For each year, all locations that are in the 1993 survey sites were used in the calculations.

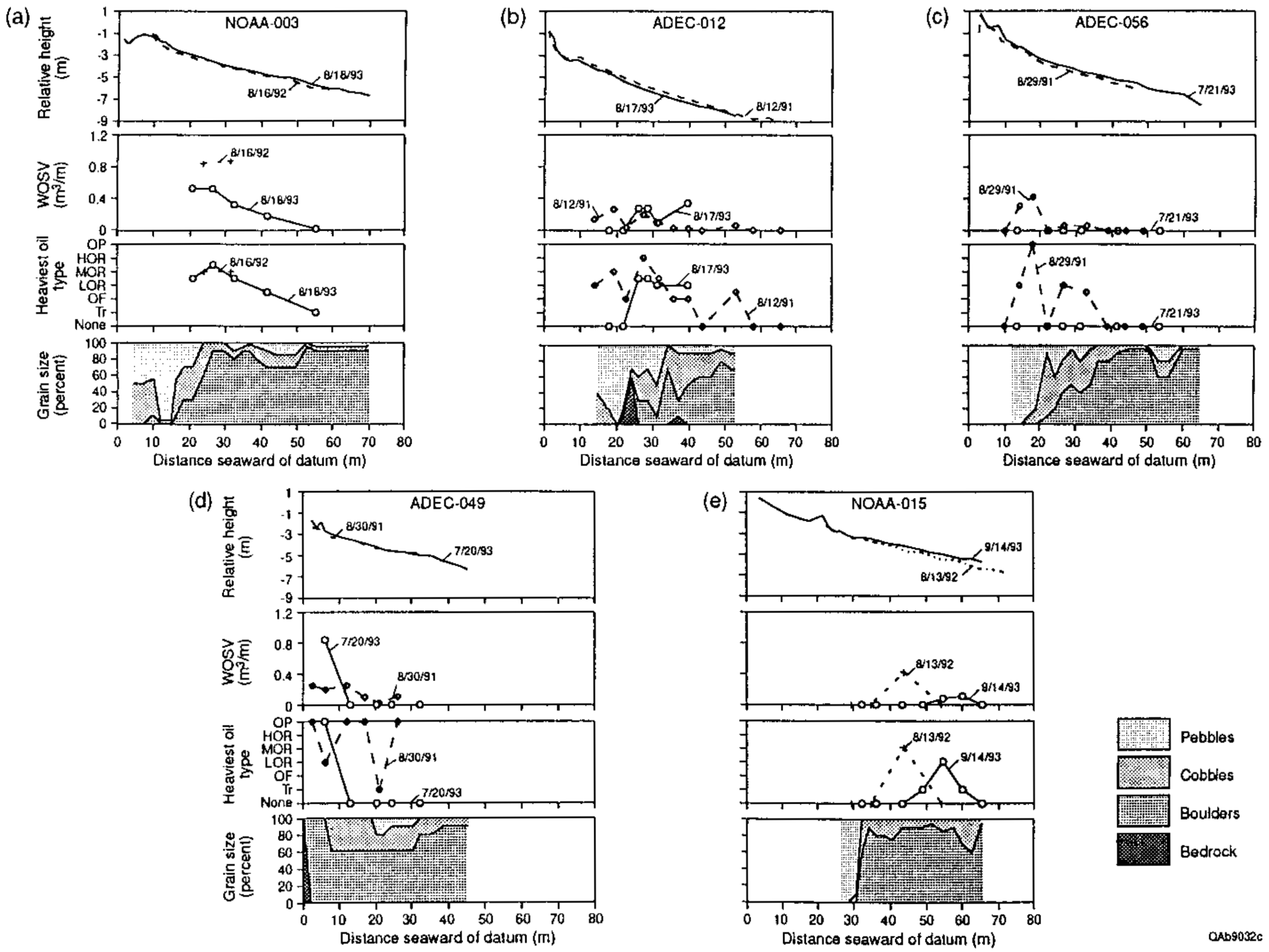


Figure 7. Transect data from high-energy, boulder and cobble beaches. See Figure 2 for locations. Relative heights are measured from datum stake or stable feature in supra tidal zone. Topographic profiles extend to approximate low-tide level. Grain size data from 1993. NOAA data from 1991 and 1992 provided by J. Michel, (RPI, Inc.). A) NOAA-3. B) ADEC-12. C) ADEC-56. D) ADEC-49. E) NOAA-15.

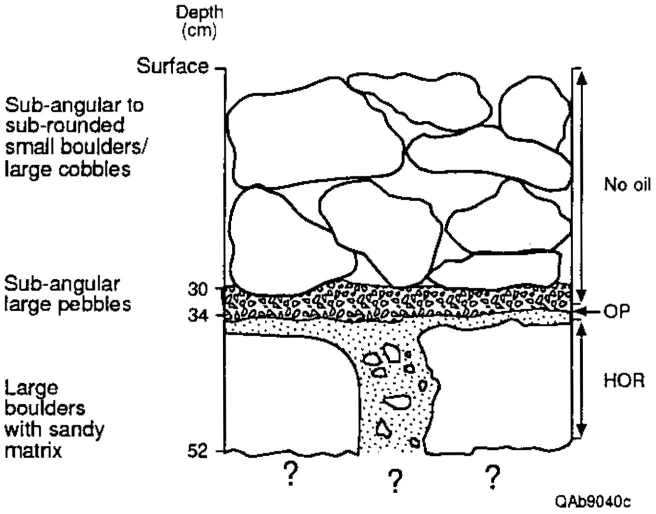


Figure 8. Stratigraphy of pit dug in the upper intertidal zone at ADEC-49 in Rua Cove. See Figure 2 for location and Figure 4 for photograph. Pit shows typical stratigraphy and subsurface oiling of armored beaches in Prince William Sound.

framework with a sandy, pebbly matrix in which the oil resided. The oil here was not treated in 1991 or 1992.

ADEC-12 is in a gravel pocket beach with bedrock outcrops. Pebble and cobble berms in the upper intertidal zone were eroded from 1991 to 1993, and MOR to OP oil was completely removed (Figure7b). In the coarser grained mid intertidal, OP/HOR reduced to MOR/LOR and the oil was 20 cm below the surface, 20 cm shallower than in 1991. NOAA-015 showed some reduction since 1992, but there was little oil in 1992 (Figure 7e).

Transect Stations: Moderate-Energy, Boulder, Cobble, and Pebble Beaches

Five beaches were measured in this category. Three of the beaches have northwesterly exposures: ADEC-004 at the head of the east arm of Northwest Bay on Eleanor Island, ADEC-125 on the east shore of Herring Bay, and ADEC-145 just south of ADEC-125 (Figure 2). Also in this group are ADEC-138 in the Bay of Isles with a northeast exposure obstructed by islands and ADEC-020 on Seal Island which is protected by bedrock outcrops and by its position on a raised bedrock platform (Figure 2).

Compared to the high-energy transects these sites had less severe oiling in 1991. ADEC-004 in Northwest Bay had no oil along the profile in 1991 and none in 1993 (Figure 9a). However, HOR below surface cobbles and boulders in the lower intertidal zone adjacent to this site was present in 1993. ADEC-125 in Herring Bay improved from LOR conditions in 1991 to just one pit with OF in the upper intertidal zone in 1993 (Figure 9b). No treatment was performed here. During the 1993 survey, the water table was very shallow (10 cm in the pits) even at low tide. Shallow ground water observed in the pits flowed down the beach. There appeared to be no significant sediment movement on the beach thus the down-beach water flow may have aided oil removal.

ADEC-145, also in Herring Bay, improved slightly but still retained black and fragrant MOR/HOR at depths to 50 cm (Figure 9c). This moderate-energy beach contains rounded and relatively well-sorted pebbles and cobbles. Layers of matrix-free pebbles are interspersed with slightly muddy, sandy pebble gravel layers. At about 50 cm depth, a pebble gravel with a muddy matrix formed a distinct contact that the oil did not penetrate. No treatment was performed here.

ADEC-138 in the Bay of Isles reduced from LOR and MOR conditions across the profile in 1991 to OF and Tr in the mid-intertidal zone in 1993 (Figure 9d). MOR persisted, however, in the upper intertidal zone. In 1993, very hard AP covered 5% of the upper intertidal below the high-tide berms. This is about the same amount of surface oil reported in 1992 but less than in 1991 when there was a 20% coverage across a wider area. The surface oil was reported as soft AP and SOR in 1991 and 1992, thus some weathering occurred. This transect, which has a northeasterly fetch and abundant sediment supply from a nearby stream, aggraded 30 to 60 cm across the mid and lower intertidal zone from 1991 to 1992. Slight erosion occurred from 1992 to 1993, but there was still a net accretion since 1991. The upper intertidal portion of the profile where AP was present in 1993 remained stable since 1991. Removal of oiled-sediment took place in 1991 and to a lesser degree in 1992. The cleanup activity may have at least partly caused the lower elevations in 1991.

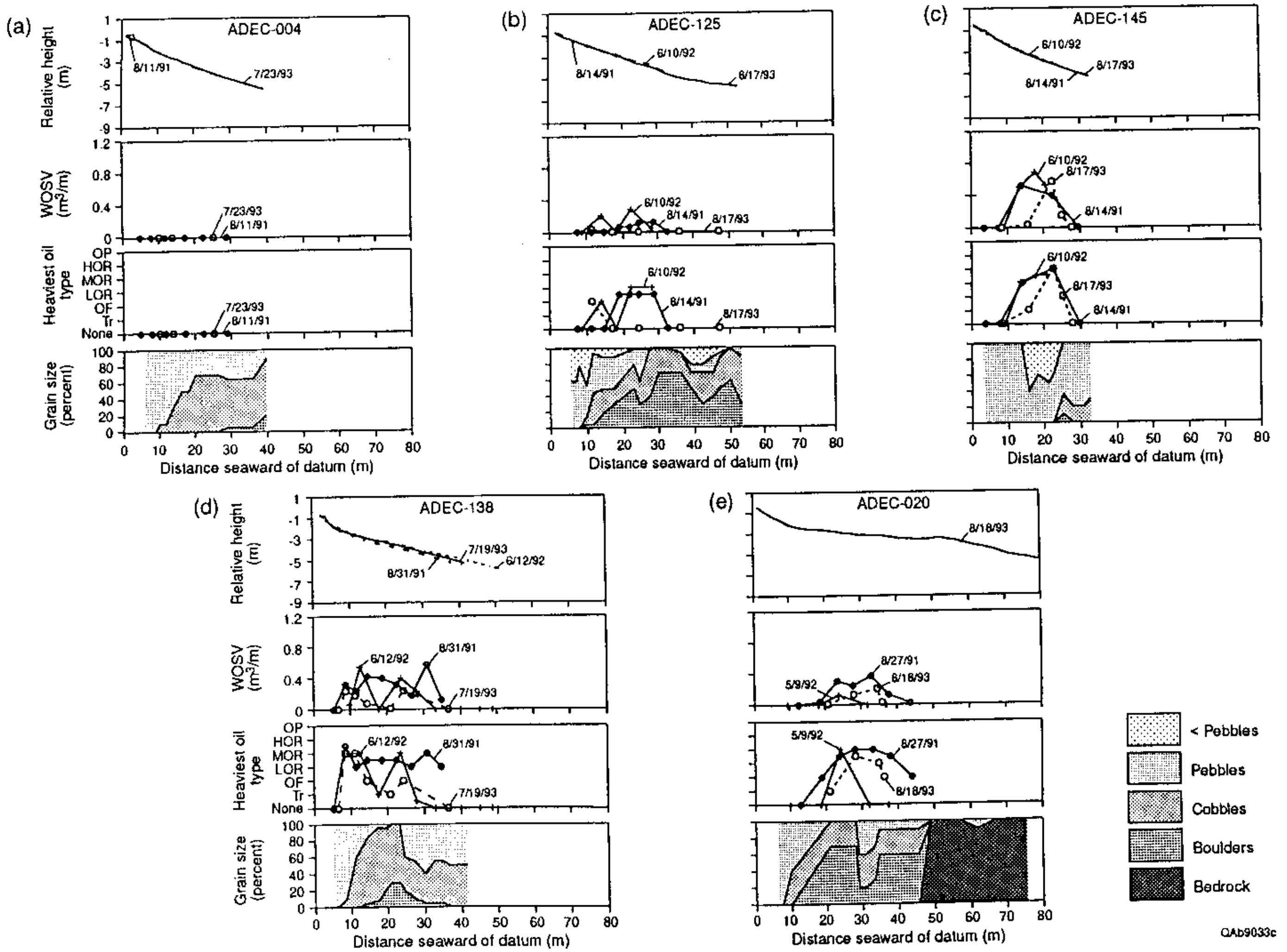


Figure 9. Transect data from moderate-energy, boulder, cobble, and pebble beaches. See Figure 2 for locations. Relative heights are measured from datum stake or stable feature in supra tidal zone. Topographic profiles extend to approximate low-tide level. Grain size data from 1993. NOAA data from 1991 and 1992 provided by J. Michel, (RPI, Inc.). A) ADEC-4. B) ADEC-125. C) ADEC-145. D) ADEC-138. E) NOAA-20.

The raised beach on Seal Island at station ADEC-020 improved slightly from MOR to LOR and MOR (Figure 9e). Gravel adjacent to the transect and in more sheltered areas, however, retained HOR oil. Treatment in the form of oiled-sediment removal, raking, spot washing, and wiping in 1992 was an important factor in reducing the oil at Seal Island.

Transect Stations: Sheltered Set-Aside Sites

Two set-aside sites (sites intentionally left untreated for the study of natural oil degradation) in sheltered locations were measured. NOAA-013 is a sheltered boulder, rubble shoreline in Herring Bay, and NOAA-006 is a raised bedrock platform with a rubble veneer in the west end of the Bay of Isles (Figure 2). There is some confusion on the status of NOAA-006 as a set-aside site and some manual removal may have occurred there in 1990 or 1991 (Michel and Hayes, 1994). NOAA-013 contained OP and HOR in 1992 on the upper boulder-dominated part of the profile (Figure 10a) (Michel and Hayes, 1993a and b). By 1993, the oil lenses had reduced to LOR and MOR and had decreased in thickness from 25 to 15 cm. The topographic profile did not change from 1991 to 1993. The oil on NOAA-006 was surface AP and shallow (<10 cm) subsurface HOR underlying asphalt crusts; apparently no improvement occurred here since 1991 (Figure 10b). Michel and Hayes (1994) also reported black, hardened AP with underlying soft, medium brown oil at this site in 1994.

DISCUSSION

Surface Oil

Table 3 shows that the total area affected by AP, MS, and SOR increased from 15,009 m^2 to 20,558 m^2 (37%) from 1992 to 1993, and that the average size of an oiled area increased from 121 m^2 to 174 m^2 (44%). An actual increase in this amount of oiled area is unlikely. Inspection of field data and discussions with 1992 surveyors indicate that the 1992 survey generally covered smaller areas or determined smaller dimensions for the same locations compared to the 1991 and 1993 surveys. It was not possible to account for this when determining common locations for comparison of surface oil. The constancy of the average percent oil cover (Table 3) and the relatively small decrease in the number of locations with oil from 1992 to 1993 compared to 1991 to 1992 strongly indicates a significant decrease in the rate of removal of surface oil. Even if the area with oil was actually twice that measured in 1992 (highly unlikely), the amounts would still show a significant decrease.

There was a large decrease in the amount of surface oil from 1991 to 1993, by about one half. Many sites, however, showed little or no change, and the rate of change decreased in 1992. Decreases in the amount of surface oil are attributable to manual removal and raking in 1991 and 1992. This conclusion is reinforced by the lack of any improvement since 1991 at the set-aside site in the western part of the Bay of Isles (NOAA-006 transect station, Figure 10b). Numerous boulder shorelines along the limbs of pocket beaches, such as on the east side of Eleanor Island (EL106B, Figure 2), that may or may not have received treatment also showed no measurable change. Large boulders and orientations of the beaches along limbs of pocket beaches form relatively low-energy environments that prevent erosion of the oil by waves. Boulders and steep beaches also hinder access by cleanup crews. Where surface oil did show significant reduction, it

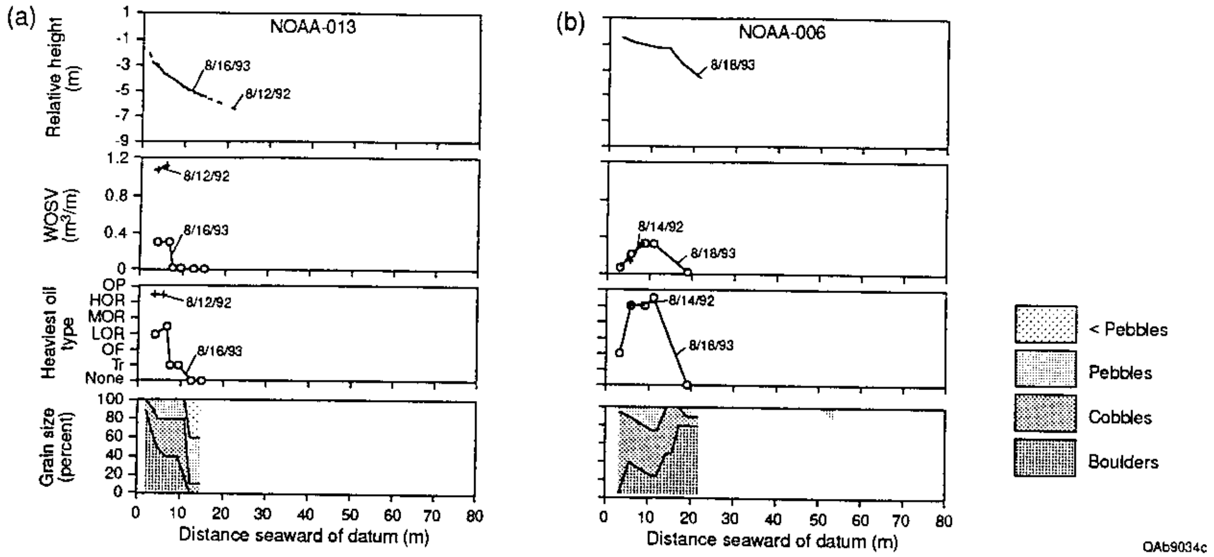


Figure 10. Transect data from sheltered set-aside sites. See Figure 2 for locations. Relative heights are measured from datum stake or stable feature in supra tidal zone. Topographic profiles extend to approximate low-tide level. Grain size data from 1993. NOAA data from 1991 and 1992 provided by J. Michel, (RPI, Inc.). A) NOAA-13. B) NOAA-6.

was along finer-grained beaches (small cobbles or finer) where AP and SOR was manually removed and raked, such as at ER011A on southern Elrington Island and KN132B along the western shore of Herring Bay, Knight Island (Figure 2).

Surface oil amount and distribution in 1993 were both a function of natural protection from waves and surface water flow and difficulty in performing cleanup. By 1991, most of the surface oil resided as AP and SOR between mid- to upper-intertidal large boulders along low-, moderate- and high-energy shorelines (Table 2) (Figure 4b). AP was also present on the upper intertidal surfaces of sheltered pebble and cobble beaches and bedrock (Figure 4c). It is important to note that even though a shoreline may have an overall high-energy setting, surface oil survived in sheltered subenvironments formed by large boulders, bedrock outcrops, and bedrock fractures. By 1992, most of the surface oil easily removed by natural and unnatural means had disappeared. Reduction from 1992 to 1993 was incremental and mostly related to treatment. There was probably a small decrease in the amount of surface oil for at least several years after 1993.

Subsurface Oil

From 1991 to 1993, there was a remarkable reduction in the amount of subsurface oil in Prince William Sound. The WOSV parameter, OP/HOR oiled sediment volume, and the number of oiled locations indicate that subsurface oil decreased by at least 50% and possibly by as much as 90% (Table 4). The volume of oiled sediment decreased less because some of the oil reduction is caused by a reduction in oil concentration only, such as a constant oiled-sediment volume of OP reducing to LOR. There also appears to have been slowing in the rate of reduction from 1992 to 1993 compared to what occurred between 1991 and 1992 (Table 4). Although the surveys detected a significant amount of natural subsurface oil reduction, considerably more reduction and a greater percent reduction occurred at treated versus nontreated locations (Table 4). In 1991, approximately 41% of the remaining volume of OP/HOR sediment was mechanically tilled and more was manually removed. This treatment had a significant effect on oil reduction. During 1992, only light manual raking, which did not address buried oil, was conducted. The slowing in the rate of oil reduction, therefore, is caused by less treatment occurring in 1992 than in 1991 and the natural entrenchment of remaining oil. Rates of oil reduction since 1993 are likely even less.

The shift in relative percents of the various oil concentration categories also supports the interpretation for a significant reduction (Figure 5). For sediment containing oil, there was a consistent shift toward lower oil concentrations from 1991-93. The large decrease in relative OP amounts from 1991 to 1992 is probably mostly caused by targeted and aggressive treatment of OP locations in 1991. The 1993 distribution shown in Figure 5 is more even than in earlier years because of the following: (1) the persistence in 1993 of recalcitrant OP and HOR that was not effectively treated and did not noticeably degrade; (2) the degradation of HOR and MOR to LOR causing a relative increase in the amount of LOR; and (3) the complete degradation of OF/TR.

Figure 6 displays a shift in the relative amounts of subsurface oil by energy setting for locations at the 1993 survey sites. In 1991, most of the heavy subsurface oil resided in high-energy locations, but by 1992, most of this oil was in moderate-energy locations, which continued to be the case in 1993 (Figure 6). This trend occurred despite the fact that in 1991 only 28% of OP/HOR sediment volume in high-energy locations was mechanically tilled compared to 72% in moderate-energy locations. The trend is explained by (1) more natural reduction occurred at high-energy locations than at moderate-energy locations and (2) high-energy locations responded to tilling better than moderate-energy locations. This is because after tilling wave and tidal energy is required to actually release and disperse the oil. . Low-energy locations also responded to treatment better than moderate-energy locations. This is likely because of relying on oiled-sediment removal instead of tilling for treatment of low-energy locations.

The shift in oil setting illustrates that much of the heavy, recalcitrant oil is in moderate-energy locations where energy levels are high enough to prevent fine-grained sediment from decreasing permeability and thus preventing subsurface oil penetration, but not high-enough to cause significant sediment movement. For this reason, these locations have not responded to treatment or natural processes as well as other locations. These locations are typically along large boulder-dominated limbs of pocket beaches and in bedrock- and boulder-sheltered areas along otherwise high-energy shorelines. In these settings, local wave shadowing has prevented natural or unnatural physical removal. They also occur along overall moderate-energy shorelines where oil resides in porous sediment below the level of sediment erosion since the spill. Transect ADEC-145 and the area adjacent to transect ADEC-4 are examples

Transect station ADEC-49 is an example where subsurface oil remains in a protected area along a high-energy shoreline (Figures 4a, 7d, and 8). Boulders derived from the bedrock cliff backing the beach have formed a sheltered subenvironment in the upper intertidal zone. Seaward bedrock outcrops also protect the site and a surface armor (see below) has formed. Another example is the high-energy pocket beach at ADEC-56 (Figure 7c). It was completely cleaned along the transect in the middle of the beach but very large boulders adjacent to the transect still harbored heavy subsurface oil in 1993. Heavy oil in gravel-sized sediment at the ADEC-20 transect on Seal Island, an overall high-energy shoreline, was protected by its position on a raised wave-cut platform (Figure 9e). This elevated position causes the waves to break and expend most of their energy seaward of the oiled area.

Subsurface oil also remained in high-energy settings where boulders and cobbles form an armored surface layer and where the subsurface sediment are permeable to oil. Hayes and Michel (1991) presented a conceptual mechanism for the formation of armor. On poorly sorted, high-energy beaches, wave energy frequently exceeds what is required for incipient motion of all particle sizes. Small particles, however, are sheltered by large particles, but intermediate-sized particles are removed. This allows a coarse armor or lag to form over finer particles. Transects NOAA-3 and ADEC-49 (Figures 4a and 8) have armored surface layers that are typical of the high-energy cobble and boulder beaches in Prince William Sound. Two to 4 layers of cobbles and boulders overly a 2 to 10 cm layer of pebbles. Below the pebble layer, a cobble and boulder framework with a sandy matrix occurs. The oil can readily penetrate the surface armor and move into the mixed sand and gravel where it is retained to depths of up to 1 m. Based on profile data, it is apparent that sediment transport has occurred at NOAA-3. The depth of erosion, however, has not reached all of the buried oil.

Other Spills and the *Exxon Valdez*

Studies of the *Arrow* and *Metula* oil spills indicate the residence time of shoreline oil in high-latitude marine environments. In 1970, the tanker *Arrow* spilled Bunker C fuel oil contaminating 305 km of shoreline in Chedabucto Bay, Nova Scotia, Canada. The oiled shorelines included low- to high-energy settings and consisted of rocky shoreline and beaches derived from glacial deposits. Responders cleaned only about 48 km of shoreline (Task Force - Operation Oil as cited in Owens et al., 1994). After 3.5 years, wave action removed most of the oil along moderate- and high-energy shorelines but little change had occurred in sheltered areas (Owens and Rashid, 1976). A survey conducted in 1992, 22 years after the spill, revealed that small amounts of oil remained on high-energy shorelines (Owens et al., 1994). Residues occurred high on the beach and high on bedrock outcrops above the reach of most wave activity. Most of the oil occurred in low-energy settings and included asphalt pavement and surface residue. Of the 305 km of initially oiled shoreline, 13.3 km (5.37%) contained some amount of oil in 1992, but only about 1 km was classified as heavy oiling. Owens and colleagues (1994) note that many of the originally heavily oiled, low-energy shorelines had no oil in 1992. They cite clay-oil flocculation as an important process in removing this oil.

In 1974, the supertanker *Metula* spilled 51,500 tons of light Arabian crude and 2,000 tons of Bunker C in the Strait of Magellan, Chile. The oil contaminated 65 to 80 km of shoreline, and no cleanup occurred. Most of the oiled shoreline consisted of exposed mixed sand and gravel beaches. Gundlach and colleagues (1982) compared surveys conducted 1 to 2 years and 6.5 years after the spill. In 1981, they found that most of the lightly and moderately oiled mixed sand and gravel shorelines exposed to wave energy were free of oil. Originally heavily oiled shorelines, however, contained asphalted-sediment pavements 10 to 20 cm thick and 10's of meters wide. Buried oiled sediment was also found. In 1981, beaches sheltered from waves had 15 cm thick, 20 to 40 m wide asphalted-sediment pavements. Little change had occurred at the sheltered locations since the spill.

In light of the persistence of shoreline oil from the *Arrow* and *Metula* it is not surprising that oil remained from the *Exxon Valdez* in 1993, four years after the spill. Oil probably persisted for at least several years at many of the locations surveyed in 1993 and may exist today. The cleanup operations from 1989 through 1992 either removed or helped prevent the formation of asphalt-sediment pavements. These pavements stabilize underlying sediment and hinder natural mechanical dispersal. They also have a weathered crust that hinders other degradation processes such as clay-oil flocculation (Owens et al., 1994) and biodegradation. The deposition of subsurface oil in Prince William Sound appears to be more extensive and persistent than that reported for the *Arrow* and *Metula* spills. It is important to note the persistence of *Exxon Valdez* oil below surface armor along moderate- and high-energy shorelines. Subsurface (and surface) oil also persisted in wave shadows formed by large boulders, bedrock outcrops, and abrupt changes of shoreline orientation such as in pocket beaches. Oil persisted in these wave shadows which may occur along shorelines with overall high-wave energy. Tilling speeded the removal of subsurface oil, but large surface armor and obstructing wave shadows lessened the effectiveness of tilling or prevented tilling in many of the locations with subsurface oil in 1993.

CONCLUSIONS

1. The *Exxon Valdez* oil spill contaminated 782 km of shoreline in Prince William Sound, and more shoreline outside the Sound, during the spring and summer of 1989. By 1991, probably less than 10% of the oiled shoreline still contained surface oil with only 1.4 km being heavily oiled. Subsurface oil, however, remained along about 36.8 km of shoreline.

2. Surface oil was discovered at all the 45 ground survey sites visited in 1993 and oil sheen was observed at many sites. The estimated area the oil would cover if it were amassed is from 2,964 to 10,230 m^2. The oil types include asphalt (AP), mousse (MS), surface-oil residue (SOR), cover (CV), and coat (CT). This oil was present at 217 locations along about 4.8 km of shoreline. AP, MS, and SOR affected about 3.7 km of shoreline and occurred at 171 locations. These are conservative estimates for the amount of contaminated shoreline in 1993 because not all of the shoreline was surveyed. The average oiled location with SOR, AP, or MS was 160 m^2 in size and had about a 23% oil cover. AP and SOR occurred in about equal amounts and are the dominate types of surface oil in Prince William Sound.

3. Surface oil decreased by about one half from 1991 to 1993. Manual removal and raking in 1991 and 1992 caused most of the decrease.

4. In 1993, surveyors measured 109 locations with visible subsurface oil. A total of 2,041 m^3 of oiled, subsurface sediment, which affected 33,749 m^2 of shoreline, was discovered. The total length of affected shoreline was about 7 km. These are conservative estimates for the amount of contaminated shoreline in 1993 because not all of the shoreline was surveyed. Subsurface oil lenses were typically 3 to 15 cm thick and occurred 5 to 30 cm below clean sediments.

5. Subsurface oil decreased by at least one half from 1991 to 1993. The rate of reduction decreased from 1992-93 compared to 1991-92. This slowing is because of less treatment occurring in 1992 than in 1991 and the natural entrenchment of remaining oil.

6. Oil amount and distribution in 1993 were a function of natural protection from waves and surface water flow, sediment dynamics, and difficulty in performing cleanup. By 1992, most of the oil easily removed by natural and treatment means had disappeared. Reduction from 1992 to 1993 was incremental and mostly related to treatment, particularly for surface oil. The rate of oil reduction since 1993 probably continued to decrease for several more years.

7. Tilling and natural removal were more effective at high-energy locations than at moderate-energy locations. The reasons for the difference are a function of sediment-transport dynamics.

8. Locations with recalcitrant subsurface oil were typically in moderate-energy subenvironments along otherwise high-energy shorelines. These locations occur along boulder-dominated limbs of pocket beaches and in bedrock- and boulder-sheltered areas. Large boulders and bedrock obstructions hindered physical treatment, and local wave shadowing at these locations prevented natural or treatment-related physical cleaning. The overall high-energy

settings, however, prevents the deposition of fine-grained (mud) matrix sediment that would have decreased permeability and oil penetration to the subsurface, as is the case along low-energy shorelines. Moderate-energy shorelines with permeable gravel beaches also retained subsurface oil where sediment erosion had not reached the depth of the oil since the spill. Moderate- and high-energy locations with boulder and cobble surface armor retained oil in the sandy matrix below the surface layer.

9. Future spill response efforts need to consider the effects of local wave shadows and surface armor on the natural retention of oil and on the effectiveness of cleanup efforts. Extra protection of these local areas during a spill and more attention during a cleanup are required to prevent the formation of recalcitrant oil deposits.

10. Process studies of beach-sediment dynamics are needed to understand the fate of shoreline oil and to aid in making cleanup decisions for future oil spills in Prince William Sound or similar areas. Much of the remaining subsurface oil resides in the sediment of moderate- and high-energy boulder, cobble, and pebble beaches that are adjusting to uplift caused by the 1964 earthquake. A lack of understanding of the sediment dynamics of these beaches contributed to a lack of appreciation of the continuing problem they would present in the *Exxon Valdez* oil spill.

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APPENDIX A: MANAGEMENT, POLICY, AND COMMUNITY ISSUES

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1 December 1993

Background

This project had a number of components: science, shoreline cleanup, interagency land and resource management, and community relations. Over time, it became a tool for tying up loose ends from the spill response that didn't seem to fit neatly into any particular restoration project or strategy.

The outstanding issues included:

- *Shoreline assessment* -- With the exception of an ADEC-sponsored comprehensive assessment in the fall and winter of 1989-90, all the shorelines surveys had been joint exercises with the U.S. Coast Guard and Exxon Corporation. Exxon, as the spiller, organized and financed these shorelines. There was considerable public mistrust of these "joint" exercises at the outset. By 1992-93 the opposition to joint surveys had narrowed to specific user or community groups. The 1993 restoration survey was intended, in part, to address these credibility questions by making this a government-led survey of affected shorelines.

- *Land and resource management* -- Response surveys tended to minimize non-scientific or technical issues associated with affected shorelines, such as subsistence use patterns and perceptions, recreation and tourism, and other services injured by the spill. This survey was intended to give agency personnel some post-cleanup perspectives on continuing impacts to these services or activities.

- *Shoreline cleanup* -- The cleanup, like the survey work, was organized and financed by Exxon, and key user groups continued in 1993 to question the effectiveness or the commitment of Exxon work plans and Exxon personnel. The people of Chenega Bay, in particular, continued to insist that more cleanup could and should be done. The 1993 restoration survey was intended to also provide the public with a public-sector assessment of the practicality of more cleanup.

- *Community relations* -- The community of Chenega Bay asked that the survey be expanded to include about 80 sites adjacent to Chenega Corporation uplands or areas used by residents.

- *Science* -- The shoreline surveys during the response provided mostly qualitative information that led to qualitative decisions and conclusions. Exxon had financed some attempts at quantitative analysis about the decrease in oiling at sites affected by the spill. The 1993 restoration survey included an attempt to make some more independent, semi-quantitative analysis of changes in oiling over time.

Exxon, Coast Guard, and Chenega Bay Involvement

The Trustee Council voted to expand the survey participants beyond the state and federal agencies serving as natural resource trustees. Exxon representatives, the U.S. Coast Guard, and community members (primarily Chenega Bay) were asked to participate.

Exxon was responsible for its own labor and transportation costs to and from Anchorage. Although the civil settlement allowed Exxon to deduct its expenses in 1991-92 from future payments to the trust fund, that was not the case in 1993, since the settlement covered Exxon's *response* costs only, and this project was under the restoration regime. Exxon, like all assessment participants, was provided with transportation to and from the home port or the work area, plus berthing space and food on the research vessel.

Coast Guard personnel served as advisors on the feasibility of continued cleanup, especially regarding potential releases from any extended cleanup activity.

Chenega Bay residents participated as advisors on subsistence and land use patterns, and as the major private landowners in the area. On May 17, 1993, leaders from Chenega Bay submitted a list of 82 sites the community members wanted to be included in the shoreline assessment. The Trustee Council included these sites in the 1993 shoreline assessment. This presented some technical and logistical issues.

Although 12 of the Chenega sites were already on the work plan list, the rest were not. Most of the sites had been surveyed by response teams and been recommended for no further treatment or assessment, some as far back as 1990. Therefore, according to the methodology for site selection, they had been deleted from subsequent assessments. Since we used essentially the same methodology in 1993, these sites were not on the work plan list for full ground survey. They were, in fact, unlikely places to find residual oiling, which conflicted with the principal goal of the 1993 assessment, which was to locate and describe residual oiling. We had to find a reasonable way to be responsive to public concerns without compromising the technical validity of the project. In addition, we had to find a reasonable way to visit more than twice as many sites as planned while staying within the original budget.

We decided to conduct the additional surveys in phases, using a helicopter to give us more mobility, and using a much smaller crew to minimize personnel costs. We agreed to look at highest-priority sites first, and visit as many as possible in between the scheduled, vessel-based surveys.

Transition from Response to Restoration

The project was led by the Alaska Department of Environmental Conservation and included both the Coast Guard and Exxon, however, authorities and roles for all were different than during the response phase.

Neither the DEC nor the Coast Guard was operating under their pollution control authorities based in state and federal law. During the response, these agencies led assessments designed to guide specific remediation action on the shorelines oiled during the spill. The guidelines for remediation were grounded in state and federal statutes and rules that say, essentially, that cleanup shall continue until technology has reached its limit, or until continued cleanup is more environmentally disruptive than leaving the pollution in place. (The Coast Guard, in addition, has some more explicit guidelines regarding the cost-effectiveness of a given remediation action.)

That was not the case in 1993. The response phase ended in June 1992, and authority for any actions on shorelines affected by the spill devolved to the various trustee agencies. The DEC project manager coordinated the effort, but did not carry the same kind of broad authority as an on-scene coordinator; he was, rather, operating as a general coordinator for the Trustee Council agencies, which were in turn assessing shoreline conditions as they might relate to specific agency management or restoration goals. The DEC was designated lead agency largely because it was the only trustee agency that had detailed cleanup information area-wide. The Coast Guard was serving as a technical advisor, and because the Coast Guard personnel assigned to the project had additional detailed knowledge of the response. Exxon was invited for similar reasons.

In approving the shoreline assessment for 1993, the Trustee Council made clear that it wished the project to follow as closely as possible the methods and data reporting systems used during the response.

Therefore, the DEC oil spill response staff selected sites for assessment based on the last reported oiling conditions. The initial list of 52 shoreline segment subdivisions included 40 of the subdivisions that had appeared on the 1992 Final Shoreline Assessment Project (known as FINSAP) conducted jointly by the DEC, the Coast Guard, and Exxon. An additional 12 sites were included because of distinctive oiling or cleanup conditions, proximity to high-priority or well-known areas, or because of incomplete oiling information that raised questions about actual conditions in 1993. This was consistent with previous surveys, especially beginning with the 1991 May Shoreline Assessment Project (or MAYSAP).

At the end of the 1992 response season, DEC staff went over the field data from that year and listed approximately 50 shoreline sites that might be included on future assessments, if any. This was standard practice during the response; the intent was to flag potential trouble spots that ought to be either monitored or treated the following season.

It is important to note that this methodology was developed with remediation as the driving force. None of the response surveys, with the possible exception of the 1989-90 fall/winter state-sponsored assessment, were intended as a compilation or documentation of *all* oiled shoreline. The survey list for each subsequent year was made up of those shorelines on which:

a) remediation was possible or likely,

b) there was a question about the accuracy or completeness of last-recorded data, or

c) there was some special agency or public concern.

Therefore, the absence of a given shoreline segment from a subsequent survey list did not necessarily mean there was no longer any oil there, it meant, rather, that treatment was not likely for some reason. The reasons ranged from accessibility of the oiling, weather or logistical concerns, environmental or archeological sensitivities, or even a relative judgment about whether the residual oiling was "bad enough" to warrant treatment. While this worked for purposes of planning response activities, the methodology for selecting survey sites was not likely to produce an accurate picture of specific oiling conditions throughout the spill area.

At the start of this project, we had two general options for selecting sites. If documenting *all* the residual oiling from the *Exxon Valdez* spill was the goal, we would have had to go back to original oiling reports, then sift through subsequent survey development records to determine which sites "dropped off" because there was little or no oil, and which were deleted because of access or other complication not directly related to actual oiling conditions. This is certainly possible, but the budget and time frame allotted for the project made this impractical.

Therefore, we decided to work from the DEC 1992 post-assessment list, with the goal of documenting and describing the oiling conditions at sites that had the longest and most extensive history of being "hot spots" during the response. For the purposes of practical information, preliminary policy-making, and limited extrapolation, this was a useful, achievable and cost-effective goal. The methodology was not likely to produce that accurate picture of all remaining oiling, but it could give the public and policy-makers a good sense of how things were changing and what one could expect to see - or not see, for that matter - on a visit to Prince William Sound.

Management and Budget

The Trustees had allocated up to $520,700 for the project, but added an additional $15,000 in spending authority to cover transportation and associated costs incurred by the U.S. Coast Guard during its participation in the assessment. Actual total expenditures amounted to less than $400,000, with the surplus being returned to the trust fund.

Field operations began June 4, 1993, and ended September 27, 1993. The field work was divided into seven phases that corresponded roughly to the times of the month when the tides were at their extremes. This procedure dated back to the early days of the response. The goal was to make sure that crews surveyed a given set of shorelines when the tide retreated far enough to expose the lowest stretches of the intertidal zone.

This was important because many of the shorelines were originally oiled during a period of very high and very low tides in April 1989. Generally, through 1992 at least, response crew supervisors tried to schedule as much work as possible when the tidal stage was no more than seven feet above mean low water. This was critical when there was a considerable amount of oiled area in the middle and lower intertidal zones.

This was somewhat less important in 1993, as oiling had decreased or disappeared in many low and middle intertidal areas. However, we stuck to the lowest tide periods for the sake of consistency, occasionally making an exception when past oiling data suggested that most of the remaining oil was in the upper- or supratidal. But for the most part, the survey phases were defined by those 7-8 day stretches when there were minus tides, or low tides that were a foot or two above mean low. This gave us a potential 14-16 field days per month, under ideal conditions.

The sites in the work plan were scattered throughout the western Sound from Perry and Lone Islands in the north to Latouche, Elrington, and Evans Islands in the south. We used a single crew and vessel and worked two low tides per day when weather and daylight permitted. Generally, there were 3-4 days at the beginning of each cycle when we could work two tides.

The weather was extremely cooperative from June through early August. We did not lose a single day to weather during that stretch, a fact that was as amazing as it was advantageous. Cruises were usually scheduled over a full 7-8 days of the available tide window, but we were able to complete each session's tasks 1-2 days early until the weather began to turn in mid-August (as it tends to do in the Sound).

We worked primarily from the M/V Pacific Star, a 65' LOA, Coast Guard inspected vessel. The vessel slept 10 comfortably but could accommodate more, if necessary.

The vessel had enough fuel capacity and speed to transit extensive stretches of the Sound either overnight, or between tides, so that we were not greatly restricted in our scheduling by distance or time. From Whittier, we could make Herring Bay and the northern Knight Island Archipelago in about 4-5 hours; the Gulf of Alaska crossing from Seward to Chenega Bay, Sawmill Bay, Evans Island, took 4-5 hours; most everything in between on the western side of the Sound was within four hours' running time.

Generally, we were able to schedule our site visits so that we could always complete two sites per day, and sometimes three when they were especially close together or not too complex in their oiling conditions.

We used helicopters for four clusters of site visits, flying out of Homer for outer Kenai Peninsula sites, Valdez for two days of community surveys, and out of Anchorage for the rest. We used the helicopters primarily when we had to finish several sites in a short time, and the vessel could not move us around quickly enough. We used Anchorage-based float planes to shuttle crew members in and out when unrelated tasks within their own agency required them to come out after the beginning of the cruise, or come in early. Usually we had one shuttle flight per cruise to change out several crew members.

If the Trustee Council decides to do further assessments of this type, I recommend building the schedule and logistical structure somewhat differently.

- **I would schedule the project for May 15 to July 15.**

  This is usually the most dependable period for good weather in the Sound. It also is the "lightest" time of year, with the longest available daytime windows. This makes it most possible to work two tides in reasonable lighting conditions.

- **I would use a smaller crew - no more than 4-5 people at the most.**

  For policy reasons we had a larger crew - sometimes as many as 10 people. However, the size of the areas we are surveying and the limited number of tasks involved make it difficult to keep that many people busy during the entire 3-5 hours in each field shift. Four trained people is just about right: two to observe and record data and two to dig and fill pits, and conduct other general ground survey observations.

- **Regardless of crew size, I would stage from a Prince William Sound location or port.**

  We began using Whittier as the staging port later in the summer. It was a shorter drive from Anchorage to Portage (rather than Anchorage to Seward), and leaving from Whittier cut out the 4-5 hour Gulf crossing from Seward. Leaving from Seward usually meant that each cruise included 1-2 extra days of travel and crew downtime.

- **I would use a helicopter instead of a vessel (if using the smaller crew), and I would return the crew to a port in the Sound each evening.**

  A helicopter would allow this smaller crew to work more sites, spaced further apart, on each tide, which would help scheduling of the project overall. Under this scenario, one could schedule a more intense, although shorter field season to fit within the optimal 60 days from mid-May to mid-July.

  I also think it would increase overall productivity and reduce crew fatigue, and provide managers with some flexibility to change crew members in or out at relatively low cost, and to deal with extended stretches of bad weather. If you knew you were going to be in the middle of a week of marginal weather, you could just send people home to their regular jobs rather than leave them in the field, unable to work. This would also mean that you wouldn't be paying transportation or charter costs on days you weren't able to fly.

- **I would be more flexible in scheduling at the outer edges of the extreme tide periods, and I would schedule at least some of the work at some of the sites during higher tides.**

  At a number of the sites, the remaining, documented oiling is relatively high up the beach. If there is not real statistical or quality-control reason to make every visit at the lowest tide, I would schedule work during periods that would have been considered marginal in 1989-92. This, again, would allow you to schedule a more intense, but shorter field season and make for a more cost-effective operation.

Notes on Methodology and Data Collection

The survey team was the same type of multijurisdictional cooperative that operated during the spill response itself. It included a mix of trustee agency representatives, major private landowners, the U.S. Coast Guard, and Exxon.

In theory, everyone was to come along on every survey; as a practical matter, some agencies chose to participate on a spot basis, or not at all. In most cases, the crew included at a minimum 3-4 DEC environmental specialists, one land manager from the Department of Natural Resources, an area ranger from the U.S. Forest Service, a pollution control specialist from the U.S. Coast Guard, an Exxon employee or contract specialist, and a marine biologist under contract to Exxon. Most, if not all the crew members had one or more seasons' experience on the Exxon Valdez response.

NOAA contributed technical staff on two of the cruises, and the Chenega Corporation sent a representative on most occasions when the survey sites were adjacent to corporation uplands, or in the general vicinity of the village. Dr. James C. Gibeaut, under contract to the Trustee Council, was the project technical advisor on geomorphology and accompanied the crew on two of the cruises. DEC staff led the crews on the shorelines, scheduled the work, recorded the data, and coordinated comment from other field representatives.

We used as a guide oiling data going back to initial field observations made by state, federal, and/or Exxon survey teams in the spring of 1989, and subsequent survey data at those sites. We found the most useful information to be the detailed field sketch maps made by Exxon geomorphologists who accompanied each survey team over time. These "OG maps" were, in most cases, excellent guides to locating most residual oiling at most of the sites. (Note to acronym collectors: The "OG map" relates to the title of the people making the sketches - the **O**il **G**eomorphologists.) We attempted to update each of these maps, marking both 1993 oiling conditions and any significant changes in beach profile, general physical setting, or other notable aspects of the area.

We also depended on the personal knowledge of individual crew members, several of whom had been at many of the sites - sometimes many times - over the four previous summers. All the DEC and Coast Guard staff had served throughout the spill area since 1989 and 1990, the chief Forest Service ranger assigned to the project was a member of the first interagency resource assessment teams in 1989, and DNR's representatives were either area park rangers or a resource specialist who had worked the spill response.

At most of the sites, we allowed experience, the physical setting of the site, and significant obstacles to determine the boundaries of the 1993 assessment. This was a change from previous years, when surveys were strictly limited to the discrete work sites from the season before.

This was partly a function of procedural policy, partly because of the number of sites on most surveys (the 1991 survey included nearly 600 sites), and partly because the response assessments had to take place within a short period in the spring so that the summer could be devoted to actual treatment. We did not have these kinds of pressures driving the 1993 project, and could therefore take more time to explore the sites and map them more precisely. However, most of the time we limited our ground surveys to specific areas mapped in 1992 and allowed the so-called "OG maps" of 1991 and 1992 as our primary guides.

We completed 48 of the 52 general ground survey sites on the original work plan list. Two of the sites (BP004A and SE042) were dropped for logistical or weather reasons; two study sites in the Gulf of Alaska were not logged on the data sheets because the adjacent landowner opted to do less detailed inspections. (While these Windy and Chugach Bay sites were on the study list itself, they were there because of community concerns rather than documented oiling conditions, and therefore less of a priority for data collection.) The project's technical advisor approved these field changes and did not think they would affect the data analysis.

We tried to get at the issue of producing more quantitative data by expanding the work plan to include 15 sites at which NOAA and/or DEC had previously laid out transects. These sites were selected primarily for the consistency and quality of the data over time, and were intended to add some level of quantitative analysis to the project. We completed 11 of these additional surveys, missing four because of *a)* weather, *b)* a lack of time, or *c)* conflicts with the original study list.

I note this here because it once again emphasizes the hybrid nature of this project. If one were designing, from scratch, a truly quantitative study of changes in oiling over time, the methods of site selection and survey would be significantly different than the ones we used. We added the transect analysis to the project in the hope that we could come to the Trustee Council and the public with a more authoritative description of how fast or slowly the residual oiling was changing or degrading.

At the beginning of the project, we discussed whether it was worth the time, expense, and logistical effort to collect oil samples for fingerprinting and analysis. We decided not to do this because it was not an integral part of our analysis. NOAA staff were already taking oil samples to determine the exposure of mussels to hydrocarbon contamination at beds that were heavily oiled -- but not cleaned -- during the response. Further, the hydrocarbon profile of a given sample is largely irrelevant to a tourist or subsistence user of the area.

In hindsight, it might have been a good idea to do some fingerprinting after all. Shortly after our field season began, a U.S. Geological Survey study suggested that oiling at a number of sites in Prince William Sound could be from spills long in the past. Trustee Council staff asked me to address this issue.

Without samples and data, it is nearly impossible to guarantee that the oiling conditions we documented were a result of the Exxon Valdez oil spill. However, the spill's documented trajectory, along with information from four years of previous surveys (which described changes in the oiling from fresh to weathered), suggested overwhelmingly that the oiling at the sites we visited came from the Exxon Valdez.

Of the 48 ground survey sites and the 11 transect sites, all showed surface and/or subsurface oiling.

The surface oiling consisted primarily of asphalt pavement, tar splatters, tar trapped in shales, and the chocolate-brown emulsion generally known as mousse.

On cobble beaches where asphalts were found, they generally appeared as sporadic clusters bound up with rocks and sand. These patches ranged from rock-hard and dry to some with a hard surface "scab" covering a fudge-like brown, weathered oil. We broke up these patches whenever we could during the course of the survey. Some sites, especially those with heavy initial oiling in boulder fields, showed bands of hardened tar and weathering mousse. With a few exceptions, the larger clusters of patches and bands of asphalts occurred in the upper intertidal areas, or in areas that were sheltered in some way from wave energy.

Boulder fields in areas with heavy initial impacts occasionally proved to be still heavily contaminated with asphalt and mousse. The oiling at these sites consisted primarily of large, thick patches of asphalt trapped between boulders, and mousse about the consistency of chocolate syrup. The mousse at a few sites was visible from the surface, but at many of these sites it was trapped beneath boulders and exposed only when the rocks were turned over.

The clues to subsurface oiling were not generally visible. Many of the sites with subsurface oiling had little or no visible contamination. Several sites gave off sheens at the tide came in, or as surface runoff trickled through the oiled zone. Very few sites appeared to sheen on their own. (Some sites sheened lightly after we had dug pits or turned over rocks.)

All the sites we visited had oiling data from 1989 through 1992. The original oiling conditions in April and May after the Exxon Valdez can be compared to successive site visits in 1990, 1991 and 1992, and the progressive changes can be tracked fairly easily. For this reason, I am confident that with a few possible exceptions, all the oiling observed can be tied to the Exxon Valdez oil spill.

First, as stated above, the impact of fresh oil coming ashore in 1989 has been documented at these sites, and progressive changes can be tracked over time.

In addition, there have been no other reports of large crude or heavy fuel spills in this area. While one cannot automatically exclude this as a possibility, had such large spills occurred, they would have had to come from large-volume carriers such as tankers or commercial fuel delivery barges. Spills from these type of carriers probably would have been reported at the time, or discovered when the spiller made port and had to account for fuel loss or use, or cargo lost. The only crude carriers in the area are the major carriers out of the Valdez terminal.

Further, the types of fuel that would leave a heavy asphaltine fraction are not generally used by the types of vessels that have transited the area in the 1980s. Diesel and gasoline, the primary fuels for recreational and small commercial fishing vessels are light and volatile. When these fuels do contaminate soils, they leave a different, less persistent kind of residue than a crude or heavy bunker fuel.

For these reasons, we suggest that for the purpose of analysis, a reasonable person would conclude that the residual oiling we describe is a result of the Exxon Valdez oil spill.

Field Notes

For purposes of description, I have separated the survey area into six general groups:

(1) The Northern Islands (Perry, Lone, Applegate, Culross)

(2) The Outer Islands (Smith, Green, Seal)

(3) Knight Island North (Eleanor, Disk, and Ingot Islands, Herring Bay)

(4) Knight Island Outer (The exposed eastern shore of Knight)

(5) Bay of Isles

(6) The Chenega Area (Evans, Bettles, Elrington, Latouche Islands)

The Northern Islands.-- We assessed six sites in this area: two on Lone Island, two on Applegate, and one on Perry. This is a relatively busy, multi-use area of the Sound that receives most of its traffic from the port of Whittier. The area is easily reached by small recreational or commercial vessel from Whittier, and the islands are within the ferry and commercial marine corridor to Esther Island hatchery and Valdez. There is a long, documented history of recreational and commercial tourism use at Applegate and Perry Islands.

Until last year, there was a small trespass sauna at Applegate; there is trash and other evidence that several sites have been frequently and recently used as camp sites on the island. Perry Island is part of a well-known kayak tour route, and we noted several trails leading either into the uplands or across island to other beaches. There is also a commercial oyster farm now in the twin bays that cut deeply into the island.

This area had some of the heaviest initial impacts from the Exxon Valdez spill, and was the scene of some of the earliest shoreline cleanup efforts.

We found two small areas of subsurface and surface oiling at the Lone Island sites. One was in a boulder field, the other in a small pocket cove with substantial bedrock outcrops that break wave energy. The Applegate Island sites were largely free of oil, with the exception of a few areas of very hard and persistent tar and asphalt packed between leaves of thin shale that has been tilted vertically and exposed along the shorelines.

There is also obvious evidence of scientific study at the Applegate coves, in the form of barely exposed rebar and leftover flagging that presumably defined study sites or marked transects. Some of the rebar is in the middle and lower intertidal and could present a hazard to kayaks, inflatables, of skiffs coming ashore at these well-used recreational anchorages.

The Perry Island (PR16) site is one with a long treatment history. It was heavily oiled in 1989 and heavily worked in 1989, 1990, and 1991 with large-scale washing and mechanical tilling operations at various points in time. It is a steep, high-energy, rounded boulder and cobble beach. However, two large bedrock outcrops in the center of the site break some wave energy. Behind this outcrop, and in a boulder field to the west, there are two areas of subsurface oiling beginning about 15 cm below the surface. This oiling is not visible at the surface and was characterized in 1993 as medium oil residue. It does not appear to have an impact on recreational uses, and, due to the porous nature of the site, is a good candidate for continued improvement on its own.

The Outer Islands.-- We visited four sites in this area, two from the ground survey list and two on the transect site list. A fifth site that we originally planned to visit was deleted for weather reasons.

The two work plan ground survey sites were both on Green Island, an island of low hills and shallow, sheltered bays and coves. For an island that is relatively exposed, it has fairly high biological values, probably due to the various sheltering areas of bedrock both on the shoreline and just off the southwestern shore. Several areas were heavily oiled in 1989 and received treatment through 1991, although work had to scheduled around shorebird nesting and rearing times and other biological sensitivities. We found areas of surface and near-surface oiling at both sites we visited, and in each case the oil was either extremely weathered or primarily characterized as light oil residue.

It is also worth noting that while one crew was walking from one site to meet up with a second group at the other site, we encountered extended areas of tar and chunks of asphalt pavement at sites not on the 1993 survey list. These other sites, at the north end of the island, were last visited in 1991 for the most part. After the 1991 season, they were deleted from future surveys because it was judged that no further treatment was possible. Indeed, treatment here would have been extraordinarily difficult and probably not very effective, but the oiling is still present. Like Applegate, this area has extended areas of exposed shale bedrock that has been tilted vertically and was filled when oil came ashore and soaked the rocks. The oil is thick and weathered and tightly packed in the leaves of shale; in some areas, there were sheens on the tide pools. In a more sheltered cove to the east of this area, there were thick chunks of asphalt mixed with gravel, some of them somewhat less than a meter across and 5-8 centimeters thick.

We worked one transect at SM008, at the southeastern end of Smith Island. This is a high-energy beach made up of very large, rounded boulders and cobbles that are tightly wedged together, and occasionally mixed with sand and pebbles below the upper layers of armor. This transect had oil from the lower intertidal (just above the Fucus line) all the way to a platform just below the storm berm. I found this interesting, since the assumption early in the response was that high-energy areas would easily "clean themselves up." The evidence at this site (and several other high-energy sites on the trip, such as the site at EL107) made me question that original assumption.

We visited one site at Seal Island, SE041A, a complex site consisting of a large tide pool, an extended tombolo, tall bedrock outcrops and a sheltered platform covered with disk-shaped boulders and rocks. It has a thin gravel substrate underlain with a thick organic layer very close to the surface. There are seabird nesting sites (we observed two pairs of oyster catchers) and more than a dozen harbor seals bobbing just offshore the tombolo.

This area was soaked heavily by oil in 1989. In 1991 it was still heavily oiled and received about three days of work. The armor was removed from an area of the platform and crews used a cold sea water flush, manual agitation of sediments by rakes, and sorbent material to release and contain the oil. A smaller, similar manual operation (minus the flush) was used in 1992 on a smaller area. In 1993, along the DEC transect and in the areas adjacent to it, the thin sediments above the organic barrier layer were still substantially oiled and sheened readily when disturbed, so we dug as few pits as possible and did not stray far from the transect line. This site should be monitored further. Because of an approaching storm and the fact we were some distance from safe anchorage, we did not conduct a scheduled ground survey at SE042.

Knight Island North.-- This area includes the smaller islands of the Knight Island Group, along with Herring Bay and a small portion of the mainland to the west at Main Bay. This was an area that was heavily oiled by the initial impacts of the spill as well as what DEC termed secondary oiling, which occurred during the on-the-water recovery period in April and May 1989. Because of local currents, tides, and circulation patterns, the oil that arrived from the vessel tended to stay around this area, moving continuously in a clockwise pattern (Hull, 1989). Oil came around the island group and entered the west-facing bays, such as Herring Bay, Knight Island and Northwest Bay, Eleanor Island, and remained trapped. There was quite a bit of "saturation" oiling, as large slugs of crude and mousse came ashore and soaked area shorelines.

This area also received considerable cleanup effort early on, especially in Herring and Northwest Bays, which were protected from weather and thus provided more stable working conditions.

This area is beginning to get more recreational use, but the passage from the Whittier area to the Knight group can be tricky for smaller craft, and it requires significant fuel capacity. Still, these are popular spots to anchor up and explore, and we observed several recreational craft, tie-up sites, paths and other evidence of human visits in the area.

We visited 13 sites during ground surveys in this area, and worked an additional four transects. This area, especially within Herring Bay and at Herring Point, is one of the two areas where one could find groups of contaminated sites fairly close together.

For the amount of oil documented within Herring Bay in 1989, the overall current picture of the area seems remarkable. There are several localized areas of significant surface and subsurface oiling that should be noted, however. Near the back of Herring Bay, on an east-facing subdivision with a major anadromous stream, is KN132B. The area immediately around the stream is relatively oil-free, but moving north, there are three noticeable bands of heavily weathered, very hard asphalt mixed with angular cobbles and gravel. In the biggest band, which measures roughly 145 meters long by four meters wide, the asphalt is rock-hard and difficult to break up. It does not sheen when pieces are placed in the water, which suggests a very advanced state of weathering. There are also some remnants of a Fish and Game camp site in the adjacent uplands, including a wooden tent platform and other small shells of structures.

A cluster of pocket beaches near Herring Point makes up KN300. At each of these sites, we found areas (the largest about 100 meters square) of high oil residue buried a few centimeters below the surface. Several of the pits showing HOR were in the extreme lower intertidal, including some below the Fucus line. While this oil sheened readily, it was not immediately obvious from the surface. When peeling back the cobble armor to dig the pits, we noticed amphopods, tiny eels, limpets and other small plants and animals in the active zone above the oiled sites.

Just outside of Herring Point, at KN500A and KN500B, the crew had little difficulty finding oil in pits within the previously documented oiled zone, but most of these pits showed medium or even light oil residue. These sites were the subject of intense work in 1989 and 1990, with some additional work in 1991.

On the other, west-facing side of the bay, the crew made three site visits, one for a ground survey and two others to run transects. Both transect sites had little or no visible surface oil, and very light or no subsurface oil on the transect. A third site in between the transect shorelines was largely free of oil, but the crew did locate a thin band of subsurface oiling buried very deep (40-50 centimeters) under the cobble beach in the mid-intertidal zone.

In general, there was little visible surface oiling in the areas we surveyed, although the crew did not walk the long, steep, boulder-field foot of the bay's western shore.

We visited five sites at Eleanor Island, two within the sheltered, northwest-facing bays and the rest on the high energy shorelines on the east. Of particular note is the site at EL056C, which even in 1993 had strong-smelling, black oil buried in an area of the middle and low intertidal zone. This area did not receive much treatment, at least not in the lower intertidal, because of access and environmental sensitivities; because it is so far down the intertidal zone, it is not exposed for long. This site should be monitored in the future. Also of note was the transect at EL107, which, while not on this year's ground survey list, still showed consistent subsurface oiling under the rounded cobble armor. This site is a steep, high-energy beach that presumably gets hit fairly hard by wave action fairly frequently.

The crew located oiled boulder fields at three, mid- to high-energy sites on Ingot Island.

There was one site visit at Disk Island, DI067, which contains a large mussel bed that was heavily oiled and is the subject of additional study by trustee agencies. There was some surface oiling around the site, and heavy and medium oil residue under the mussel bed in the middle intertidal.

The crew visited two small islets in Foul Bay, just off the mainland. (These are part of a Main Bay segment, MA002.) Generally, the area looked oil-free on the surface. It was interesting to note the abundance of Fucus and other seaweeds at one of the sites, which had been cleaned aggressively with hot water in 1989. Also of note was a small tide pool at MA002A, in which workers in 1992 had cleared out rocks and agitated heavily-oiled sediments. The area still shows signs of obvious oiling - the tide pool sheens spontaneously from its outlet - but there is extensive and diverse plant and animal life within the zone.

Knight Island Outer.-- This area includes all the shorelines on the eastern shore of Knight Island, with the exception of the Bay of Isles. Four of the five sites we visited in this area are relatively exposed, and did not receive much treatment until the latter part of the 1989 cleanup season.

Due to the amount of oil that came ashore and the limited treatment (mostly manual after 1989) in subsequent years, it is not difficult to find mousse and other heavy oil residue in these boulder beaches. There are visual clues, and more oiling can be located by turning over rocks and small boulders. They have improved in their condition since 1991 and presumably weather and wave energy will continue dispersing or breaking up the oiling. However, these sites (KN211, KN209, KN213) continue to contain areas of heavy oil residue. At Point Helen, KN405A, the crew found some traces of surface oiling and various low levels of subsurface oiling along the whole subdivision. This area was very heavily oiled in 1989 and was treated aggressively through 1991. It was a particularly complex area to treat due to the fact that it was so heavily oiled, so exposed, and subject to a complicated energy pattern. Oiling here in 1993, however, appeared significantly lighter than during pre-treatment surveys in 1991.

<u>Bay of Isles</u>.-- The Bay of Isles is a visually stunning area, the entrance through a narrow, mountain-edged mouth, the mountains of Knight Island's spine rising at the back of the bay, islets scattered about the inside waters, and a variety of angular cobble beaches nestled at the foot of steep-sided, spruce covered slopes. Large slugs of oil surged through the entrance in 1989 and settled primarily on beaches in the south arm. Segments KN134, KN135, and KN136 received much of the attention of the response teams in this area through 1991.

The most publicized area was probably KN136, sometimes described as a marsh and sometimes as a lagoon. This segment actually consists of a rocky buttress and high intertidal platform that shelters a tide pool that is primarily a settling place for organic material. There is a thick layer of peat, or a similar woody compound in the basin. This peat bog is above low water and drains at low tide. It was heavily oiled and primarily left alone after experiments with treatment that included laying sheets of plywood so workers could walk into the peat without stirring up the muck or sinking oil more deeply into it by tromping through it. It still smells of oil, and the platform in the supratidal is still heavily contaminated, although quite a bit less so than in 1989 and 1990. The bog itself is still oily. We dug not conduct a ground survey in the bog, although we did run a transect near the back of it. There isn't much one can do about this area other than leave it alone. It is improving slowly, judging from previous data and crew member observations.

It is interesting to contrast this site with adjacent beaches, especially at KN134 and KN135, both of which received aggressive and continuing treatment throughout the response period. These sites seem to show considerable improvement; KN135 showed a few pits with light to medium oil residue, and a transect site in the area showed similar characteristics. While one could not tie this improvement to treatment efforts in a quantitative manner, it is worth noting that these areas are sheltered, low energy sites that are not likely to "clean themselves up." It is my opinion that the treatment here was well worth it, at least in terms of releasing and recovering oil. Judging from the angular nature of the cobble beaches, I have some question about whether weathering and wave energy alone (or primarily) effected the big changes we see here.

<u>The Chenega Area</u>.-- This is a tough area to assess, because the technical issues and the social and economic issues are closely intertwined.

Based on my conversations with village representatives, it is obvious that they are not satisfied with the condition of several clusters of beaches, regardless of how they compare to conditions at sites in other areas of the Sound. We visited 16 individual sites in the area, and in a two-day survey July 6-7, using a helicopter for access, we visited almost all the accessible shoreline on Chenega Island.

This area contains some of the most persistent, heavy- and medium-oil residue concentrations that we found on this assessment.

Some of the areas are small and localized, such as those at Bettles and northeast Evans Island, and some are more broadly and consistently oiled, especially the area within Sleepy Bay and the headlands on either side of this bay on Latouche Island. There are long bands of oiling in boulder fields and buried in the mid- to upper intertidal areas of Sleepy Bay's northwest shores. At least two of them are more than 100 meters long, and indeed, one can find residual oiling at the surface and in the subsurface throughout this northwestern area defined at LA20B and LA20C. The boulder fields at LA20B are scarred with areas of pavement, and the mid- to upper intertidal areas of LA20C have easily accessible areas of subsurface medium and high oil residue. Outside the bay itself, on the arms at LA21 to the northwest and LA15 to the northeast, oiling occurs sporadically - and occasionally significantly - throughout the segment. (Again, aggressive treatment may have combined with a favorable physical setting at some sites - notably LA15C and LA20A - to produce the best results over these past five seasons.)

These areas will probably continue to improve over time, as others in the western Sound have. However, this does not appear to be acceptable to the people of Chenega Bay, who hunt and fish and beachcomb in the area adjacent to their village on a day to day basis. They have expressed continuing interest in accelerating the improvement through treatment of some kind.

The most heavily oiled areas are significant when compared with others on the survey, and they are near the village. This exacerbates the social and economic effects of the oiling. Perhaps because villagers can locate oil so close to home, they often perceive that the oiling is broader or more extensive - hence the request to survey those 70 additional sites. In fact, our experience on the community surveys tended to support the information on file, which showed that these sites were largely free of oil. However, there are lingering doubts among certain village representatives and they hope that a remediation effort will reduce or eliminate problems both real and perceived.

In contrast, other Chenega sites appear oil-free. Chenega Island, which had two concentrations of heavily oiled subdivisions at the north and south tips, had very little, if any visible oil. Subsurface pits showed little or no oil at most sites (with the exception of a mussel bed at the north entrance to Dangerous Passage).

Restoration and Remediation

In a purely technical sense, beach cleaning at this point - especially by manual means - would likely produce only incremental results. A handful of sites lend themselves to manual work, and the amount of work is probably low relative to the time, money, and effort required to conduct it. Agency representatives from ADNR and the U.S. Forest Service expressed some interest in limited remediation at some sites, but this did not appear from their comments to be a high priority. In Chenega, however, remediation remains a priority.

There may be good policy reasons for pursuing remediation at sites, whether that be in the vicinity of Chenega Bay village or at recreational use sites at Applegate Island. If the Trustee Council wishes to continue treatment, I suggest three practical options for remediation as a restoration strategy:

- **Clean up debris.**

We frequently came across rebar, signs, back-stakes, flagging and other evidence of study work at shorelines throughout the area. It would be worthwhile to find out who has marking out there and whether they are still using it. If they're not, it ought to be pulled up.

- **Manual cleanup of selected, high priority sites.**

I estimate that one crew, working 30 field days, could complete manual work at 10-12 sites around Chenega Bay if the Trustee Council felt this was an appropriate policy action.

- **Manual remediation of mussel beds that remain oiled.**

This is largely a biological assessment issue that this project did not address. NOAA is studying this problem under a separate restoration project, and there may turn out to be sound biological reasons for removing these sediments rather than waiting for them to disperse naturally. If that turns out to be the case, we have determined that manual remediation at some of the sites is technically feasible, as long as any releases of oil are properly contained and cleaned up.