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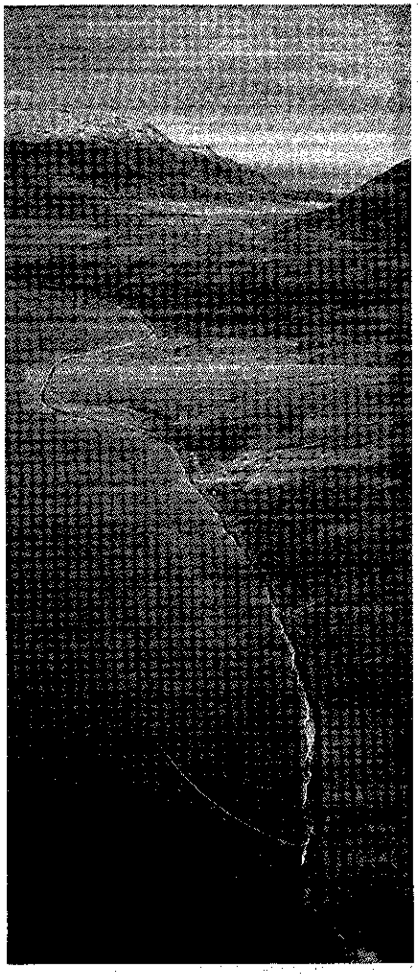

The Fate and Persistence of Stranded Crude Oil: A Nine-year Overview from the BIOS Project, Baffin Island, N.W.T., Canada

Report EPS 3/SP/4
March 1992

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Gary Sergy
Manager, Western Regional Office
Technology Development Branch
Conservation and Protection
Environment Canada
4999-98 Avenue
Edmonton, Alberta
T6B 2X3

Cette publication est aussi disponible en français sous la titre "Sort et persistance du pétrole brut échoué : Survol sur neuf années du projet BIOS, Île de Baffin (T.N.-O.), Canada", à l'adresse ci-dessous.

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controlled plots. Total Petroleum Hydrocarbon determinations alone do not describe the beach, but they may be used to describe specific beach features.

Natural removal of backshore oil occurs only when the oil is fresh and exposed to the air if no other forces are applied. After the first year of exposure, very little change was observed in the oil content of backshore sediments. Weathering was also limited to the first year. After ten years, most of the spilled oil remains on the untouched plots. Mixing the spilled oil into the backshore using a rototiller resulted in reduced loss of oil to evaporative processes. The tilling had the effect of making surface oil, which can be slowly weathered, into subsurface oil, which is somewhat protected from weathering.

Résumé

*Le projet de déversement de pétrole à l'île de Baffin, ou projet BIOS (*Baffin Island Oil Spill*), s'est déroulé entre 1980 et 1983 au cap Hatt, à l'extrémité nord de l'île de Baffin au Canada. Il consistait en des déversements expérimentaux de pétrole sur une plage arctique et des secteurs de l'arrière-plage. On a mis à l'essai diverses méthodes de nettoyage, mais certaines parcelles ont été laissées intactes et ont fait l'objet d'une surveillance régulière. Au terme du projet, il restait du pétrole sur un certain nombre de parcelles et sur la zone intertidale; ces lieux ont été surveillés périodiquement jusqu'en 1989. On a ainsi pu bâtir une base de données à long terme concernant les déversements de pétrole côtiers. Ces informations permettent de tirer certaines conclusions claires, malgré certaines lacunes apparentes.*

Les conditions et les lieux de l'opération visaient à reproduire un scénario de mazoutage relativement grave mais réel dans un climat essentiellement froid et sur une plage à faible énergie de la houle, recouverte de gravier et de galets reposant sur des sédiments plus fins et moins perméables.

Dans la zone intertidale, une quantité importante du pétrole superficiel a été éliminée par des processus naturels. Tout d'abord rapide, le rythme d'élimination a considérablement ralenti à mesure qu'était enlevé le pétrole «libre» inaltéré disponible. La superficie mazoutée équivalente (SME) ne représentait plus que 28 % de la superficie initiale après deux saisons (environ cinq mois) d'eaux libres, et 13 % après huit saisons. Après deux ans, la plus grande partie du pétrole résiduel avait formé un revêtement bitumineux dans la zone intertidale supérieure. Après huit ans, la forme du pétrole résiduel variait de relativement fraîche à fortement altérée.

Dans la zone intertidale, les concentrations de pétrole subsuperficiel mesurées à des endroits prédéterminés se sont avérées faibles. L'observation visuelle d'autres endroits sur la plage a révélé qu'une certaine quantité de pétrole subsuperficiel frais et mobile demeurait présente après huit années.

Les nombreux relevés effectués sur la zone intertidale mazoutée permettent de dégager un certain nombre d'indicateurs de tendances, dont la longueur mazoutée, la superficie mazoutée, le volume de pétrole et le volume des sédiments mazoutés. Le plus utile (et le plus économique) des indicateurs concernant l'évolution

de l'état des littoraux mazoutés est la superficie mazoutée équivalente (SME), qui combine le pourcentage mazouté et le pourcentage de la superficie couverte. Durant toute la durée du projet, on a procédé à quelque 2 000 mesures des hydrocarbures pétroliers totaux (HPT) à partir d'échantillons prélevés dans ces parcelles et sur la plage. La variabilité des résultats, attribuable à des variations dans la teneur en hydrocarbures et la granulométrie des échantillons, était élevée même dans les parcelles bien contrôlées. Les mesures des HPT ne suffisent pas à décrire la plage, mais elles peuvent servir à décrire certaines de ses caractéristiques.

L'élimination naturelle du pétrole d'arrière-plage ne se produit que si le pétrole est frais et exposé à l'atmosphère en l'absence d'autres forces. Après la première année d'exposition, le contenu en pétrole des sédiments d'arrière-plage avait très peu changé. Le processus d'altération s'est également limité à la première année. Après dix ans, la plus grande partie du pétrole déversé demeure sur les parcelles laissées intactes. Le brassage du sol de l'arrière-plage au moyen d'un motoculteur a ralenti l'élimination du pétrole par évaporation en transformant le pétrole superficiel (qui peut s'altérer lentement) en pétrole subsuperficiel, qui devient en quelque sorte protégé contre l'altération.

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Acknowledgements

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Section 1

Introduction

1.1 Background

From May 1980 to August 1983, the Baffin Island Oil Spill (BIOS) Project sponsored field research addressing oil spill response alternatives to a slick threatening or contaminating remote nearshore areas. The work took place at Cape Hatt, Baffin Island in the Canadian Arctic (Figure 1). A variety of experimental spills were monitored to quantitatively assess and compare the fate and effects of chemically dispersed crude oil and a beached crude oil slick, as well as the effectiveness of shoreline cleanup techniques.

When the BIOS Project was completed, residual oil remained on small backshore plots (in Z-lagoon) and on a larger sheltered intertidal beach (called Bay 11). These provided sites for continued long-term monitoring of the fate and persistence of stranded oil. The follow-up studies were funded by the Environmental Studies Research Fund in 1985, and by Environment Canada in 1985, 1987, and 1989. Surveys using consistent techniques have thus been conducted in 1980, 1981, 1982, 1983, 1985, 1987, and 1989.

1.2 BIOS Project Publications

The results of the four-year, multi-disciplinary BIOS Project have been published in a series of 24 scientific papers in a supplementary issue of the journal *Arctic* (Volume 40, Supplement 1, 1987). This issue includes an overview of the project (Sergy and Blackall, 1987).

As part of one experiment in 1981, 15 m^3 of aged crude oil was released onto the surface of the nearshore water and allowed to strand on the low wave energy, mixed sediment beach. The stranded oil was subsequently left to natural self-cleaning processes. The fate and persistence of the oil was monitored, in terms of concentrations and composition changes, in four major environmental components: the water column (Humphrey *et al.*, 1987b); the intertidal beach sediments (Owens *et al.*, 1987a; 1987b); the subtidal sediments (Boehm *et al.*, 1987); and the tissue of selected benthic invertebrates (Humphrey *et al.*, 1987a). Biodegradation of oil was monitored in the intertidal (Eimhjellen and Josefson, 1984) and in the subtidal sediments (Bunch and Cartier, 1984). The migration of oil from the beach into the subtidal sediments is considered in Owens *et al.*, 1987c. The effects of oil upon subtidal communities were reported in Boehm *et al.*, 1987, and the effects on benthos were reported by Cross and Thomson, 1987, and Cross *et al.*, 1987a; 1987b.

In another experiment, intertidal and backshore control plots were established at three locations in 1980 and shoreline countermeasure experiments were conducted in 1981 and 1982. The experiments evaluated selected countermeasure techniques and monitored the fate of the stranded oil. (Owens and Robson, 1987b; Owens *et al.*, 1987d.)

The shoreline programs associated with the BIOS Project began in 1980 and continued until 1989. The programs addressed three

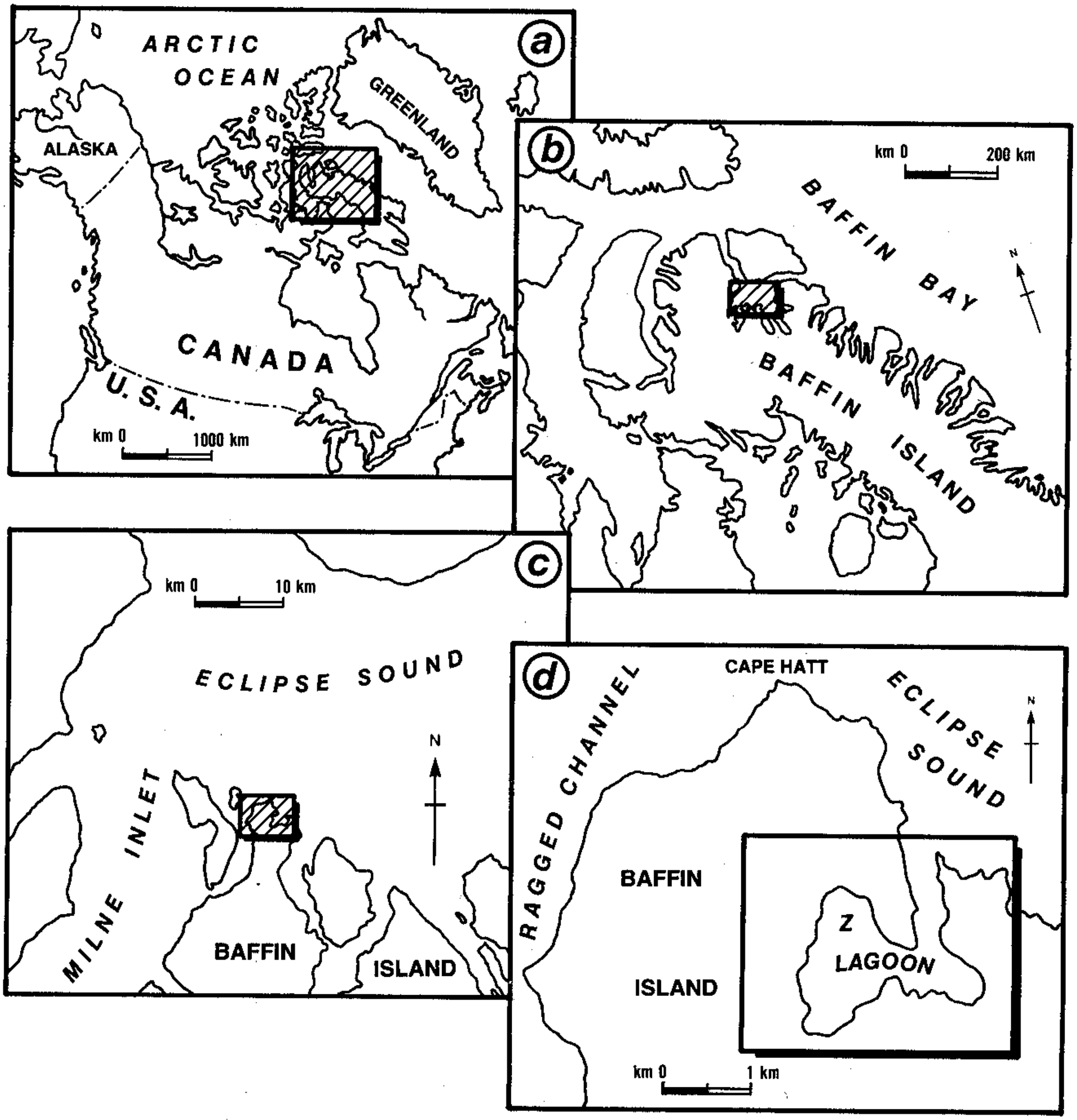


Figure 1 Cape Hatt and Z-lagoon Study Area

issues: the fate and persistence of oil stranded in the intertidal zone; the fate and persistence of oil stranded in the immediate backshore (where it could be stranded during a storm surge); and the effectiveness of cleanup countermeasures. Initially, the emphasis was on countermeasure effectiveness, as well as monitoring the fate and persistence of the oil. After 1982, no further countermeasure experiments were conducted, but the monitoring programs have continued. Three sites retained oil in 1989: the Backshore Control plots on Crude Oil Point in Z-lagoon; the Backshore Experiment plots at Bay 106; and the beach at Bay 11. This work has generated a considerable library of data reports and publications.

In addition to the formal publication of the BIOS Project results referenced in this subsection, the results have been presented in a series of working reports, many of which include original data. These reports are listed in Table 1.

In August 1989, a field investigation was carried out that involved resampling and resurveying of (a) the oiled control and experimental plots at the two sites in the Z-lagoon area, and (b) the oiled beach at Bay 11 in Ragged Channel. Observations and measurements were made and samples of contaminated sediments were systematically collected in order to provide a data set that would be comparable with previous field studies at these sites. The samples were later analyzed chemically to determine total petroleum hydrocarbon concentrations and to evaluate the degree to which the oil had been weathered. The results of the 1989 survey are presented in this report, with an overview of the fate and persistence of crude oil stranded for nine years on intertidal and backshore arctic beaches.

The results of the monitoring programs from 1985 to 1989 were presented at the 13th Arctic Marine Oil Spill Program Technical Seminar (Humphrey *et al.*, 1990) and at the 1991 International Oil Spill Conference (Sergy *et al.*,1991; Humphrey *et al.*,1991).

Table 1 Reports on Shoreline Programs

Subject	Year of Study	Report
Shoreline studies	1980	Woodward-Clyde Consultants, 1981
	1981	Owens *et al.*, 1982
	1982	Owens *et al.*, 1983
	1983	Owens, 1984a
	1985	Owens *et al.*, 1986a
	1987	Owens and Humphrey, 1988
Chemistry	1980	Green, 1981; Boehm, 1981
	1981	Green *et al.*, 1982; Boehm *et al.*, 1982
	1982	Humphrey, 1983; Boehm, 1983
	1983	Humphrey, 1984; Boehm *et al.*, 1984
	1985	Owens *et al.*, 1986a
	1987	Owens and Humphrey, 1988

These papers compare the findings of this and other oil spill monitoring programs.

Environment Canada conducts a broader program to develop a data base on the fate and persistence of stranded oil. As part of this program, data relevant to the BIOS Project have been collected from other spill sites. These data and specific aspects of the shoreline program are discussed in the following reports.

(i) *Amoco Cadiz*: Owens and Robson, 1985; Hope and Humphrey, 1986; Owens *et al.*, 1986a.

(ii) *Metula*: Owens and Robson, 1987a; Owens *et al.*, 1987e.

(iii) Estimates of shoreline oil contamination: Owens, 1984a; 1987

(iv) Asphalt pavement formation: Owens *et al.*, 1986b; 1987c.

As this project has progressed, some of the results published in these reports have had to be re-evaluated. The most recent reports should be considered to be correct.

Study Area

2.1 The Cape Hatt Area

The shoreline component of the BIOS Project was conducted on a number of beaches in the vicinity of Cape Hatt, northern Baffin Island, N.W.T. (72°31'N: 79°50'W). Control and countermeasure plots were established in the intertidal zone in 1980, 1981 and 1982, and on the backshore in 1980 and 1982 on beaches in the Z-lagoon area on the east coast of Cape Hatt. As part of a separate study, a nearshore release of 15 m^3 of aged crude oil in Ragged Channel in 1981 was allowed to strand on a beach on the western coast of the Cape Hatt peninsula. This beach is designated as Bay 11. These areas are shown in Figures 1 and 2.

Tides in the Cape Hatt area are semi-diurnal and unequal in height, ranging from 1.0 m at neap to 2.0 m at spring tide (Buckley *et al.*, 1987). This is an ice-dominated marine environment with an average summer open-water season of 63 days per year (late July to early October). This may vary from as little as 35 days to a maximum of 90 days (Dickins, 1987). The intertidal zone is encapsulated by an ice foot and is therefore inactive in terms of physical environmental processes, i.e., wind, waves, and tides, for much of the year. The intertidal areas are biologically barren, as is common in the Arctic.

2.1.1 Z-lagoon

The Z-lagoon area is a large embayment on the east coast of the Cape Hatt peninsula which was selected for a series of different shoreline experiments. Two beach sites in the Z-lagoon area were resampled in 1989: (i) the backshore aged oil and emulsion control plots at "Crude Oil Point" (termed T1 and T2 respectively) that were laid down in 1980; and (ii) the backshore aged oil (IMC) and emulsion (IME) control and countermeasure plots at Bay 106 (Figure 2), that were laid down in 1982. The Bay 106 countermeasure plots had been mixed by a rototiller in 1982 to assess whether this mixing process would affect the rate and degree of weathering of the oils.

The Crude Oil Point plots were established on a low-angle slope (<5°) about 0.5 m above the limit of wave activity. They have not been subject to marine processes and therefore provide a non-marine environment control reference for the intertidal data. Each plot is 40 m^2 in area at a location that is characterized by sandy gravel sediments with a thin surface lag deposit of shingle.

The Bay 106 plots were laid down above the beach berm but below the upper limit of marine processes, to replicate oil that would become stranded at a very sheltered location during spring tides and/or a storm surge. These plots could therefore only be affected by marine processes at the infrequent times of such events. The maximum fetch of Bay 106 within Z-lagoon is on the order of 1 500 m, so that the plots would be affected only by small waves generated during the short summer open-water season in this very sheltered environment. The berm sediments are pebble-cobble and grade into fine-grained sands on the backshore section of the plots.

2.1.2 Bay 11

Bay 11 denotes a small beach site on the eastern shore of the Ragged Channel fjord (Figure 2). It is exposed to waves with a fetch of less than 10 km and is subject to low wave energy levels during the open-water season (wave heights usually less than 10 cm). No long-term wind data are available but observations indicate that the prevailing winds during the open-water season are from the northwest quadrant (Meeres, 1987). The beach is sheltered from the north and open to waves through a 60° arc between southwest and west-northwest and to refracted waves from the northwest.

Over the eight-year period covered by the study (August 1981 to August 1989), the beach would have been ice-free and therefore exposed to physical coastal processes for approximately 17 months. The beach is defined by two bedrock outcrops about 400 m apart and the intertidal width varies to a maximum of 50 m. A gravel-cobble ridge (an incipient boulder barricade) characterizes the lower intertidal zone and gives way landward to a trough or runnel of silt and sand. The upper intertidal zone has a sand-gravel beach face with a low cobble berm at the high-water mark. From the beach, the nearshore seabed slopes at about 4° and the poorly sorted fine-grained sediments have a mean size of 3.4 ϕ (approx. 0.075 mm).

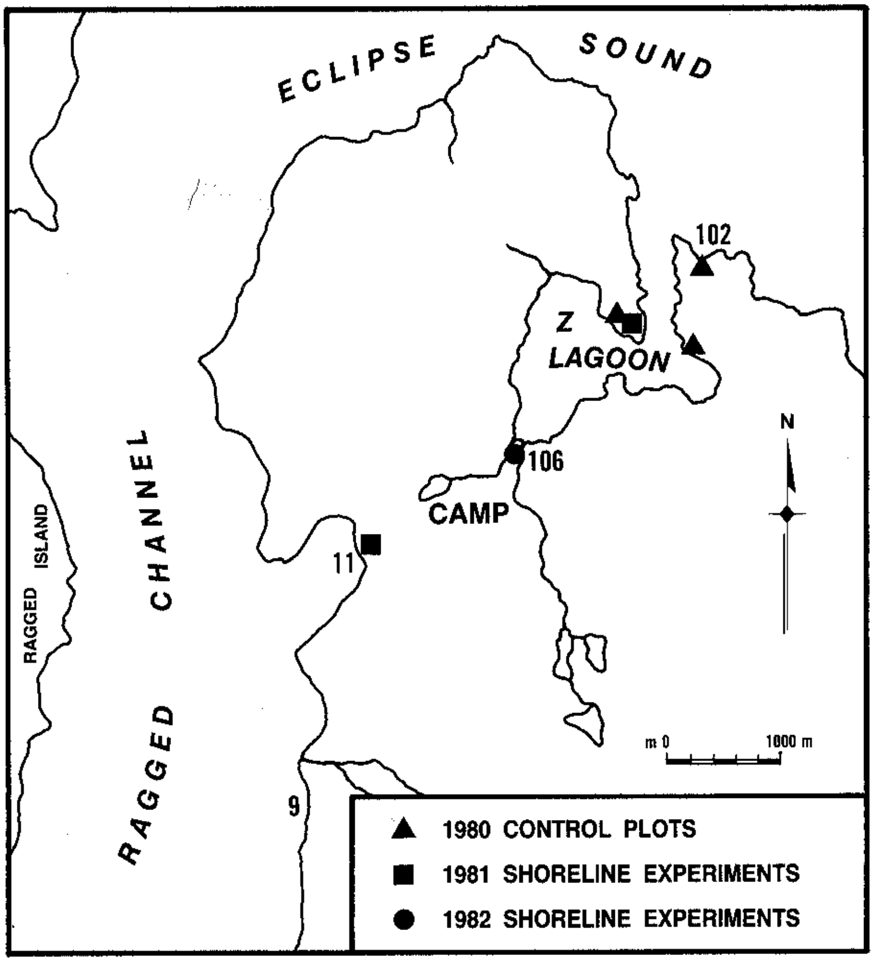


Figure 2 **Plots in Z-lagoon and Bay 11**

Methods

3.1 Application or Release of the Oil

3.1.1 Backshore Plots in Z-lagoon

Two forms of the same oil were used throughout the program: a Lagomedio crude oil that was artificially aged – 8% by weight (Dickins *et al.*, 1987) and 50% water-in-aged crude oil emulsion. The emulsion was prepared on-site by recirculating a mixture of two barrels of seawater with two barrels of the aged crude oil through a pump and tank until the desired emulsion was created. Each four-drum batch of emulsion was labelled and, in an attempt to reduce the number of variables, only oil from the same batch was used on any single plot.

Before application, a sample was collected from each batch of crude oil and emulsion for gas chromatographic (GC) analysis. The emulsion was stable over a number of days. In 1983, one attempt was made to re-emulsify two drums of emulsion that had been made up the previous year. The emulsion had broken and intensive mixing did not cause the materials to re-emulsify.

A relatively even coating of oil was applied to each plot. A thickness of 1 cm of the aged crude oil and 2 cm of the water-in-oil emulsion was applied in order to approximate a large oil spill stranded on the shoreline. Before the oil was applied, a lined trough was prepared at the base of each plot to collect any oil that would run downslope off the plot. In addition, plastic drip mats were located at the end of each plot to prevent contamination outside the designated plot area.

The application system consisted of an oil drum mounted on the back of an All-Terrain Vehicle (ATV) and connected by hoses and a pump to an oil distribution pipe mounted on the rear of the ATV. The ATV traversed the test plot and oil was distributed over a 2 m wide swath behind the vehicle. The vehicle's speed was determined by the calibrated flow rate (3.1 L/s) necessary to cover the plot with a 1 cm thickness of crude oil and 2 cm of the emulsified oil (Woodward-Clyde Consultants, 1981; Owens *et al.*, 1982).

3.1.2 Bay 11 Nearshore Release

On August 19, 1981, approximately 15 m^3 of Lagomedio crude oil, which had been weathered artificially (8% by weight), was discharged onto the water surface adjacent to the shoreline of Bay 11 (Dickins *et al.*, 1987). The period of discharge (15:40 to 21:40 hours) coincided with the ebbing tide. The resulting oil slick was carried to the shoreline by a prevailing onshore breeze and was contained within a boom attached to the north and south ends of the bay.

At the end of the discharge period (which was low tide), operations began to remove oil, which had not stranded on the beach, from the water surface by skimming and with sorbants. This oil removal continued from the evening of August 19 to 16:00 on August 21, when it was decided that there was insufficient refloating of oil from the shoreline to continue operations. By this time, four complete tidal cycles had elapsed. A total of 58 drums of oil and water-in-oil emulsion, or approximately 5.5 m^3 of oil, was recovered from the water surface. The estimated loss by dissolution during the discharge is 0.26 m^3, to evaporation during discharge is 1.95 m^3, and to evaporation over the subsequent 48-hour period is 0.45 m^3 (Dickins *et al.*, 1987). On this basis, about 6.8 m^3 of oil contaminated the adjacent beach.

3.2 Field Observations and Measurements

Field surveys were conducted in July/August 1980 in the Z-lagoon area and in July/August 1981, August 1982, August 1983, August 1985, August 1987, and August 1989 in both the Z-lagoon and Bay 11 areas. Observations were made on the visual appearance of surface and subsurface oil and external environmental disturbance, e.g., erosion or burial of oil due to wave or ice action. During each survey, colour slides were taken of the plots and of the intertidal areas and each year, except 1987, aerial colour photographs were taken from a helicopter (see Plates 1 to 4).

Surveys of the distribution of surface oil on the intertidal zone at Bay 11 were conducted along a series of 19 transect lines, set 20 m apart alongshore perpendicular to the shoreline. The lines were marked by backshore stakes so that repetitive surveys could be conducted. Visual observations were taken at a 2-m interval along each profile to record the percent oil cover to the nearest 5%; each observation therefore represents 40 m^2.

From this data, the observations were grouped into five major categories: no visible oil, 0%; light cover, 5 to 20%; light to moderate cover, 25 to 45%; moderate to heavy cover, 50 to 70%; and heavy cover, 75 to 100%. Distances along the transect lines were measured by taping in 1981 and 1982, and by pacing in 1983, 1985, and 1987. In 1989, the two-pole method of Emery (1961) was used. In 1983, cross-checking by two independent observers established the repeatability of the technique to be on the order of ±5% (Owens, 1984b).

The length of the Bay 11 intertidal shoreline where visible oil is present is determined from the mapped data. This provides a simple measure of the linear extent of shoreline contamination. The grouped data are used to provide a measure of the area and degree of contamination.

A second-stage description of the degree of contamination on the Bay 11 shore is provided by the Equivalent Oiled Area(EA), which is obtained by integrating the percent oil cover with the area. Thus, a total of nine observations (equal to an area of 360 m^2) with a 10% oil-cover would provide an EA value of 36 m^2, and five observations (equal to an area of 200 m^2) of 80% would give an EA value of 160 m^2. The EA for each set of observations is obtained by summing the individually calculated values obtained at one time. The Average Surface Oil Cover for the contaminated area of the Bay 11 beach is obtained by dividing the EA value by the total oiled area value.

In addition to the systematic ground measurements at Bay 11, the total oil cover on the beach was visually estimated each year from a rock outcrop at the northern end of the study beach, approximately 5 m above the high-water mark. In 1983, 1985, and 1987, the oil cover on the beach was also visually estimated from a helicopter flying at an elevation of approximately 100 m (see Plates 1 to 4).

3.3 Sample Collection

Sediment samples up to 2.4 L in size or subsamples that were composited later with a total volume of between 2 and 2.5 L, were collected from the surface (top 2 cm) and the subsurface (5 to 10 cm depth) of both the plots and the intertidal beach. All the samples were analyzed for total petroleum hydrocarbons (TPH) to determine the oil-in-sediment concentration and selected samples were analyzed for composition by gas chromatography.

3.3.1 Backshore Plots

The sample design for each plot was established before oiling and was based on a grid pattern. While the pattern of sample collection varied from plot to plot and from year to year, samples were always collected from a previously unsampled location within the plot. Surface and subsurface samples were collected from the Backshore Control plots (T1 and T2) at Crude Oil Point on the day the oil was laid down (August 20, 1980) and thereafter two days (August 22), four days (August 24) and eight days (August 28) after the oil was laid down. Subsequent sampling took place twice in 1981 and 1982, and on one occasion each in 1983, 1985, 1987, and 1989.

At Bay 106, the first set of surface and subsurface samples was collected on August 14, 1982, the day after the oil was laid down, from the berm and the backshore parts of each of the backshore crude and emulsion plots (IMC and IME respectively). On August 15, half of each plot was mixed and thereafter samples were collected from the berm and backshore parts of each of the unmixed (IMC-c and IME-c) and mixed (IMC-m and IME-m) sections later the same day, one week later (August 22), one month later (September 15), and on one occasion each in 1983, 1985, 1987, and 1989.

3.3.2 Bay 11 Intertidal Beach

In 1981, samples were taken three times (one day, one week, and three weeks after the release) and once during each field survey in 1982, 1983, 1985, 1987, and 1989. A surface and a subsurface sample was collected along each of three beach profiles in 1981 and along each of four profiles in 1982, 1983, 1985, 1987, and 1989 from the lower, middle, and upper one-third of the intertidal zone. This sample set was intended to provide data on changes in the total petroleum hydrocarbon (TPH) content of the sediments through time. In 1983, 1985, 1987, and 1989, additional samples were collected to provide data on specific features, particularly the asphalt pavement that had formed by 1983.

3.4 Sample Analysis

3.4.1 Total Petroleum Hydrocarbons (TPH)

The total hydrocarbon analysis by infrared spectrophotometry consisted of a solvent extraction, using Freon 113, followed by measurement of a CH_2 absorption at 2 850 cm^{-1}. The detection limit was 30 mg/kg, with a precision of 10 mg/kg at low concentrations and 1% at high concentrations. Sampling accuracy and the validity of the analytical results are discussed by Humphrey (1984) and by Owens and Robson (1987b).

3.4.2 Gas Chromatography

Extraction, fractionation, and analysis of the samples was based on the method of Brown *et al.*, (1979). From 1980 to 1987, gas chromatography with flame ionization detection (GC/FID) was used to quantify the n-alkanes and isoprenoids, whereas selected parent and alkylated benzenes and polynuclear aromatics were quantified by gas chromatography with mass spectrometry (GC/MS). In 1989, both fractions were analyzed by GC/MS, and reconstructed ion chromatograms of the alkane fractions were produced.

3.5 Weathering Ratios

The gas chromatographic analysis provided data to determine diagnostic weathering ratios. The three diagnostic ratios used to describe weathering throughout the program were Saturated Hydrocarbon Weathering Ratio(SHWR), Alkane-Isoprenoid Ratio(ALK/ISO), and Aromatic Weathering Ratio(AWR). (See Table 2.) Evaporative weathering is indicated by the SHWR which approaches 1.0 as low-boiling point, saturated hydrocarbons (n-C10 to n-C17) are lost by evaporation. Biodegradation is indicated by the Alkane-Isoprenoid Ratio (ALK/ISO) which approaches 0 as the n-alkanes are preferentially depleted. The AWR approaches 1.0 as low-boiling point aromatics are lost by evaporation and/or dissolution (Boehm *et al.*, 1987).

3.6 Bay 11 Intertidal Surface Oil Budget Computations

3.6.1 Volume of Surface Oil

Two methods were developed to calculate the volume of surface oil on the beach. The first method is based on changes in the distribution of the surface oil cover, and the second involves use of the total hydrocarbon data and the total oiled area.

The first, and more simplistic approach, uses the initial volume of stranded oil and relates this to changes in the EA value. A change in the EA value from one data set to the next is considered to reflect a change in the volume of surface oil (top 2 cm) on the beach. Thus, if the EA value is reduced by half between two surveys, it is assumed that the volume of surface oil is also halved over that same period. The baselines for this method are the initial surface oil volume estimate of 5.3 m^3 on August 19, 1981 (see next paragraph) and the EA value of 4 850 m^2 when the first survey was conducted on August 26, 1981.

Table 2 Diagnostic Weathering Ratios

RATIO	DEFINITION	FRESH LAGOMEDIO	AGED LAGOMEDIO
ALK/ISO	$\dfrac{\text{Sum(n-C14-nC18)}}{\text{(Farnesane+Trimethyl-C}_{13}\text{+ Norpristane+Pristane+Phytane)}}$	2.4	2.5
SHWR	$\dfrac{\text{Sum(nC12-nC25)}}{\text{Sum(nC17-nC25)}}$	2.9	2.3
AWR	$\dfrac{\text{All benzenes, naphthalenes, fluorenes, phenanthrenes and dibenzothiophenes (DBTs)}}{\text{Phenanthrenes and DBTs}}$	4.3	3.5

The second method integrates the total hydrocarbon concentrations with the oil distribution data. The total area of the oiled beach, 8 570 m^2 in August 1981, is multiplied by the sample depth of 2 cm to give a volume of the oiled beach surface of 171.4 m^3. The weight of the surface beach material, to 2 cm depth, is a product of the volume times the assumed density of the beach sediments (1.6); 274 tonnes or 274 000 kg. As the mean oil concentration is 17 400 mg/kg on August 19, 1981, and as there are 274 000 kg of sediment, multiplication gives 4 772 kg of oil on the beach on that date. Using a density of 890 kg/m^3 for the oil, this converts to a volume of 5.3 m^3 of oil on the beach surface on August 19, 1981.

3.6.2 Volume of Contaminated Sediments

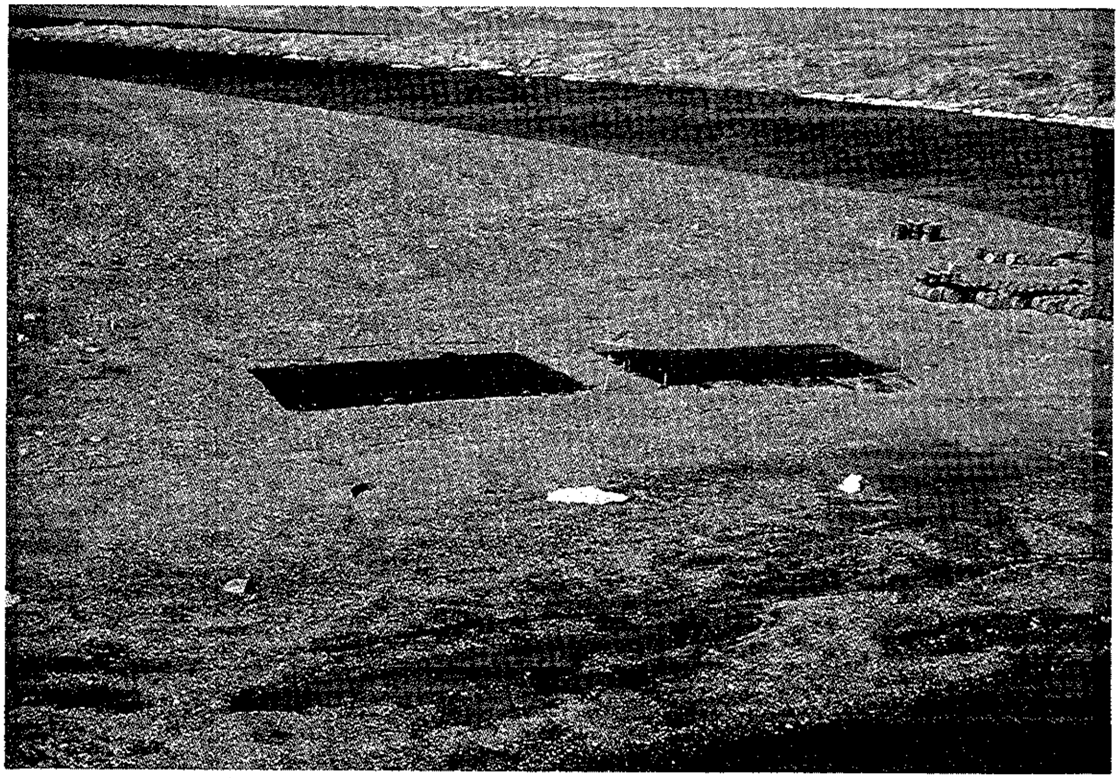
A simple volume can be calculated by multiplying the total area with an oil cover by the depth of contamination. This value reflects the total volume of oil-contaminated sediments that would have to be removed and disposed of if the beach were to be cleaned. For example, in 1985, assuming an average oil depth of 10 cm, the calculation produces an estimated volume of contaminated sediments of 440 m^3. The 10-cm depth reflects the observation that very little oil was found in the 5 to 10 cm samples and is a likely working depth for machinery during a cleanup operation.

This calculation relies on an unsupported assumption regarding oil penetration and should therefore be used with caution.

3.7 Statistical Analysis of Results

In each case, the first analysis of the TPH data was graphic. The data were plotted against time, usually days from spill. Some trends were apparent, although scatter was significant. The statistical significance of the data was tested using a further analysis.

With the accumulation of data from several years, it seemed appropriate to subject the time series to a regression analysis. The TPH data for each plot and subplot or depth stratum were regressed against the number of days from the original spill to determine if statistically significant changes were being observed using the TPH data.



a. **Backshore Control Plots T1 (right) and T2 (left) in 1981 - One year post-spill**

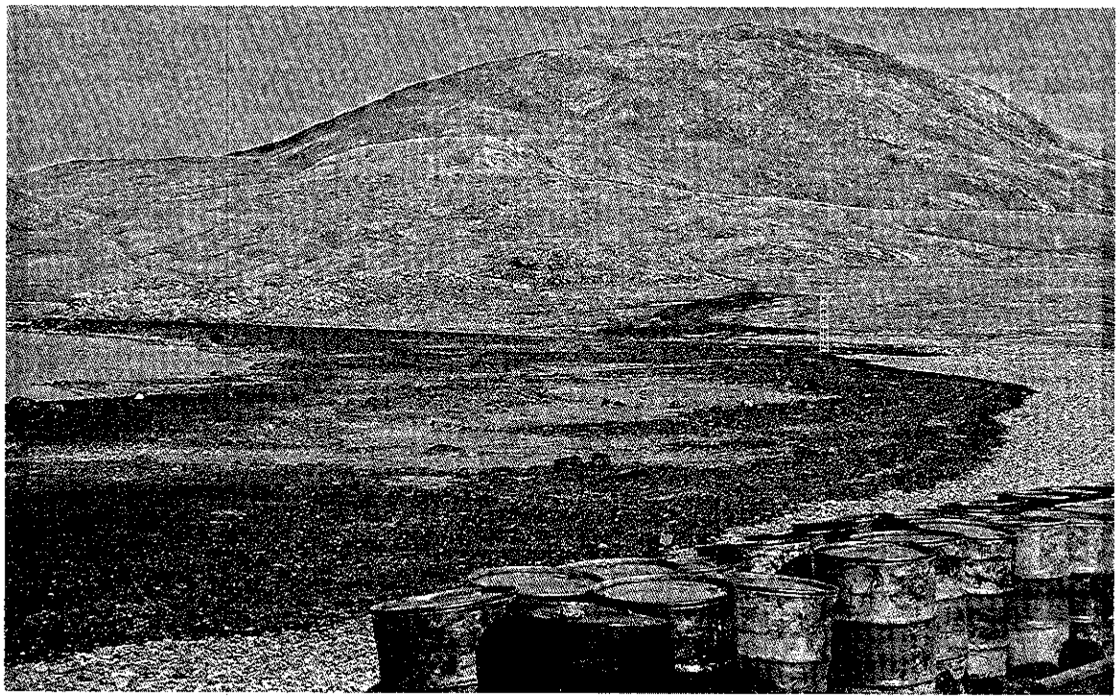
b. **Backshore Plots - Surface view in 1989**

Plate 1

c. **Backshore Plot in 1989 - Oil visible in (darker) subsurface sediments**

Plate 1 (cont.)

a. Bay 11 Aerial View - Oil stranding on shoreline in 1981



b. Bay 11 - Initial surface oil cover in 1981

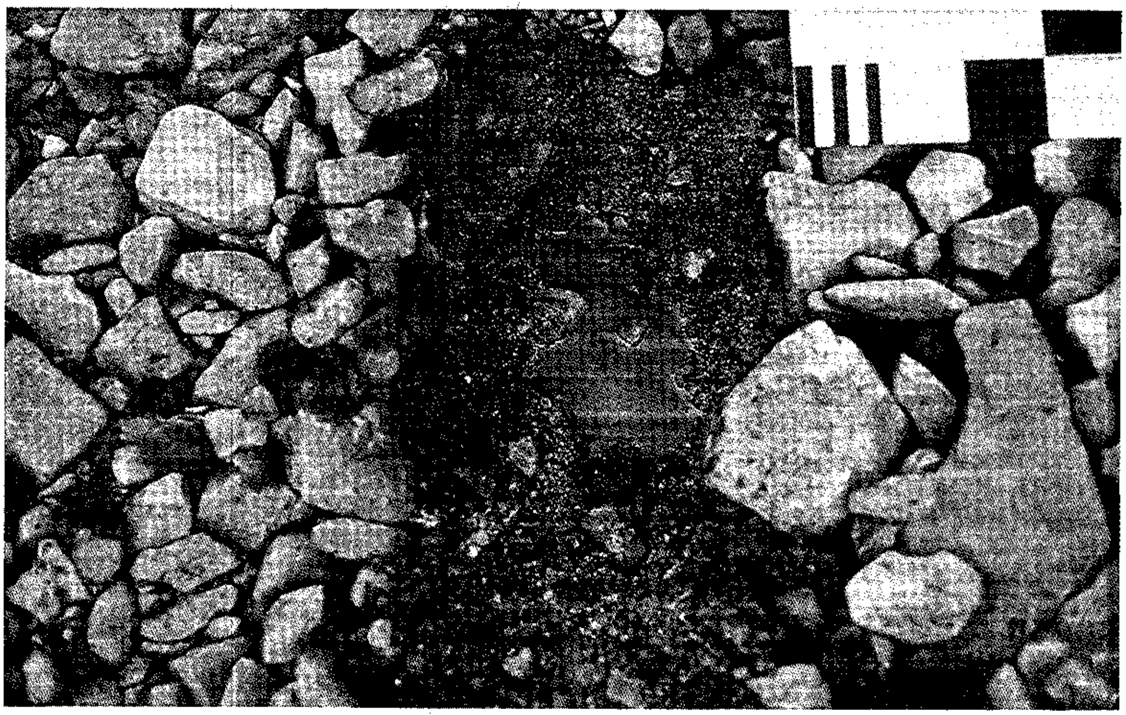
Plate 2

a. Bay 11 - Aerial view in 1989

b. Bay 11 - Asphalt pavement ribbon in upper intertidal zone (1989)

Plate 3

a. Bay 11 - Asphalt pavement oil/cobble/sand matrix (1989)



b. Oil sheen in pit dug in Bay 11 intertidal zone (1989)

Plate 4

Results from the 1980 Backshore Controls

4.1 Total Petroleum Hydrocarbons (TPH)

By 1987, the surface oil on both plots had a dark grey, weathered appearance but, by 1989, the subsurface oil was still black and relatively fresh-looking. On the crude oil plot (T1), the total hydrocarbon concentrations in the surface sediments from 1980 to 1989 indicate that the amount of oil in these sediments had been reduced (Table 3), although the graph in Figure 3 indicates that sample variance is too high for the results to be statistically significant. Much of the difference must be explained by sampling bias; the 1983 results are obviously different from other years due to the small sample numbers.

On the emulsion plot (T2), the surface oil-in-sediment concentrations were initially much lower than those on the crude oil plot and remained in the same range from 1980 to 1989 (Table 3). The data show no evident or statistically valid trends.

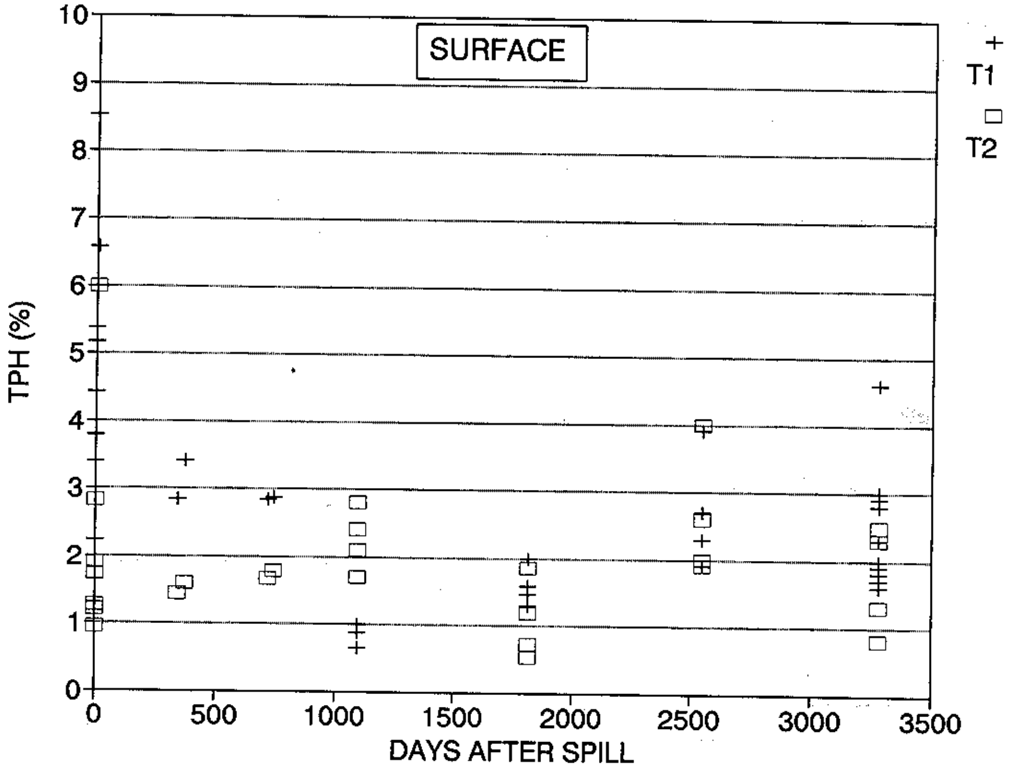
The TPH concentrations of the subsurface sediment samples on the crude oil plot (T1) were initially (in 1980) about half the surface sediment values (Table 3). After the first year, the concentrations were steady although scattered (Figure 3). The regression analysis indicates that the concentrations did not change significantly from 1981 to 1989, but remained within a band of values. The large variance within each year masks any possible changes (Table 4).

4.2 Weathering Ratios

Weathering ratios for the 1980 backshore control plots are shown in Table 5. The SHWR results for the surface sediment

Table 3 TPH Values (%) - 1980 Backshore Control Samples

DATE	T1 (Crude)		T2 (Emulsion)	
	Surface	Subsurface	Surface	Subsurface
20-Aug-80	4.0	2.3	1.3	1.5
22-Aug-80	5.8	3.0	2.0	2.7
24-Aug-80	3.4	3.5	1.3	1.3
28-Aug-80	6.6	1.7	6.0	5.8
28-July-81	2.8	2.4	1.4	2.1
29-Aug-81	3.4	2.1	1.6	1.8
10-Aug-82	2.8	1.6	1.7	1.7
02-Sep-82	2.9	1.5	1.8	1.4
20-Aug-83	0.9	1.0	2.3	0.6
11-Aug-85	1.6	0.6	1.1	0.6
11-Aug-87	2.7	1.7	2.6	1.6
16-Aug-89	2.4	0.3	1.7	0.3



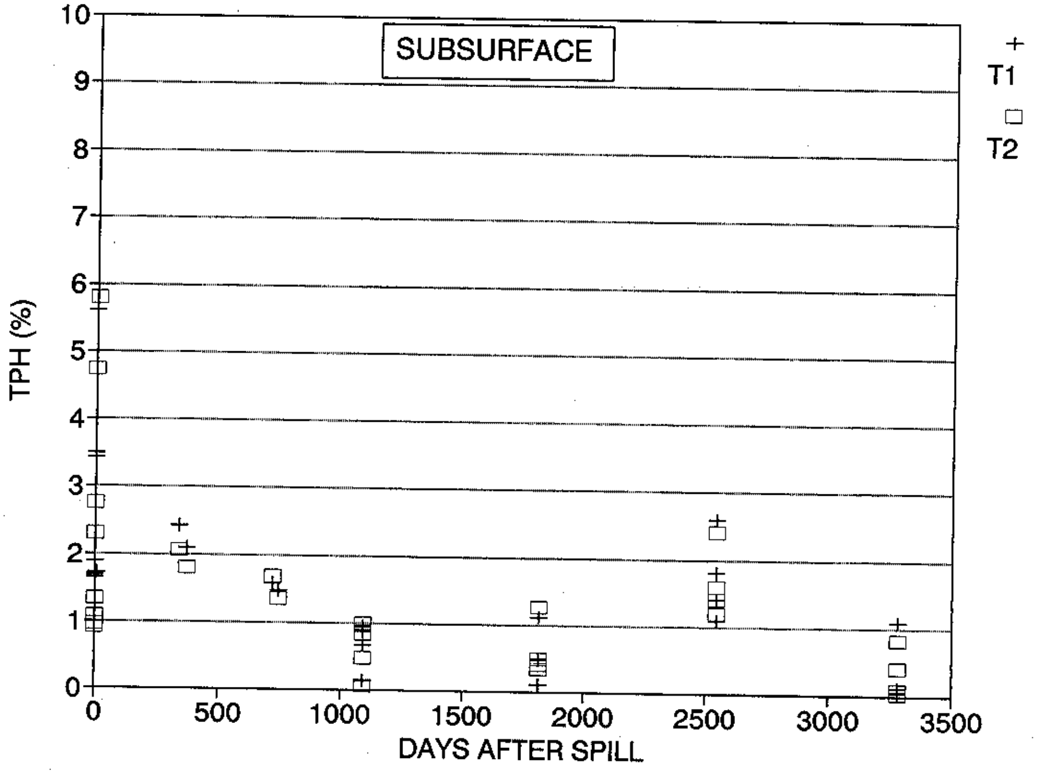


Figure 3 TPH Values (%) - 1980 Backshore Control Plots

samples on both plots show an initial lowering of values, and therefore active evaporative weathering before the 1981 sampling. Since then, the values have been relatively stable. No subsurface samples were analyzed in 1980, but results subsequently suggest that evaporative weathering rates were slower than on the surface. This is particularly true on the emulsion plot (T2) which appears to have been subject to relatively little change. (Note: the SHWR of the original batch of aged crude oil delivered to the study area is 2.28.)

The ALK/ISO ratios of the surface and the subsurface sediment samples on both plots appear to have reduced slowly over the study period. There is no evident difference in the ratios between the plots or between the surface and subsurface sediments.

The few AWR ratios that were measured indicate that by 1985, weathering on the surface and subsurface of T1 had progressed at a similar rate, whereas on T2 the subsurface sediments had weathered at a considerably slower rate than the surface sediments on both plots and the subsurface sediments on T1.

4.3 Discussion

Although the yearly data sets exhibit large statistical variances, it was concluded that the oil had penetrated the dry, somewhat loose substrate by the end of the first summer. There is little difference between surface and subsurface concentrations of oil after 1980. The oil at this site has never formed a hard surface crust or resembled an asphalt pavement. The oil content has changed little through time, with the exception of an initial decrease in the oil content of the T1 surface sediments as light fractions of the crude oil were weathered.

The trends that were apparent up to 1985 are now thought to have been affected by the sampling pattern. In reality, there has been little or no quantifiable change in the oil content of the surface or subsurface sediments after the first year of exposure. A regression analysis of the TPH data against days after the spill indicates that very little change occurred in all plots, and what change there was occurred in the first year of exposure.

As indicated in Table 3, a significant change occurred over the entire period, from 1980 to 1989, but this change occurred only in the first year, after which there was no further measurable change. In all cases, the large within-year variances observed mask any between-year changes. The rate of change is clearly very slow. Although some early samples contained high concentrations of oil, overall the plots decreased only about 0.2% each year, or about 1.5 to 2% in the first year, and not at all thereafter.

Table 4 Regression Analysis - 1980 Backshore Control Samples

	Rate of change (%TPH per annum)	
	1980 to 1989	1981 to 1989
T1 Surface	0.2	<0.1
T2 Surface	<0.1	<0.1
T1 Subsurface	0.2	<0.1
T2 Subsurface	0.2	<0.1

Table 5 Weathering Ratios - 1980 Backshore Control Samples

YEAR	T1 (Crude)						T2 (Emulsion)					
	Surface			Subsurface			Surface			Subsurface		
	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR
20-Aug-80	2.2	2.6	3.5				2.1	2.6				
28-Aug-80	2.2	2.8	3.1				2.1	2.6				
1981	1.6	2.1	2.0	1.7	2.5		1.6	2.4	3.1	2.0	2.6	
1982	1.6	2.4					1.3	2.4				
1983	1.1	1.9		1.8	2.2		1.4	2.2		2.2	2.2	
1985	1.6	2.0	1.8	1.9	2.1	1.9	1.1	1.8	1.3	2.2	2.3	2.7
1987	1.4	3.1	1.8	2.2	2.9	4.4	1.3	3.1	1.9	1.8	2.9	2.4
1989	1.4	1.8	5.1									

Results from the 1982 Backshore Experiments

5.1 Total Petroleum Hydrocarbons(TPH)

The TPH determinations for the 1982 backshore experiments are shown in Tables 6 and 7. In the surface control plots, the oil concentrations decreased over time for both the crude oil (IMC) and the emulsified oil (IME), but no significant change occurred for the mixed surface oils or the subsurface oils. The same results are shown graphically in Figure 4. For the surface control values, much of the change is determined by the decrease in concentration of outlying values. Again, the variability within each year, as seen in Figure 4, tends to mask between-year changes or subtle long-term trends.

5.2 Weathering Ratios

Weathering ratios for samples from the 1982 backshore experiments are shown in Tables 8 and 9. The SHWR values for surface samples show no major trends other than a reduction in the ratio on all plots after the 1982 data set. The ratios for subsurface samples were higher in 1983 than those from the corresponding surface samples, with one exception (IME control, backbeach) and the ratios were lowered on the crude plots between 1983 and 1985, but remained high on the emulsion plots. The mixing activity had no apparent effect on the rate of evaporative weathering in the short- or long-term periods covered by these results.

The ALK/ISO ratios for both surface and subsurface samples provide no major indication of biodegradation. The few AWR values, obtained largely from the control plot samples, show some reduction in values on the crude control plot, but little or no evidence of a trend on the emulsion samples. The AWR loses meaning with later samples, as high values may be obtained as the

Table 6 Surface TPH Values (%) - 1982 Backshore Experiments

	IMC				IME			
	Control		Mixed		Control		Mixed	
DATE	Berm	Back beach	Berm	Back beach	Berm	Back beach	Berm	Back beach
14-Aug-82*	11.0	2.4	5.7	2.4	1.2	1.8	1.7	4.2
15-Aug-82	6.7	2.1	2.3	1.3	0.8	3.5	0.9	1.2
22-Aug-82	8.9	3.8	1.9	1.5	0.9	4.0	1.4	2.5
15-Sep-82	5.7	3.3	3.1	1.8	0.5	6.5	0.9	1.7
20-Aug-83	6.2	2.2	3.1	1.1	1.1	1.4	0.7	1.1
10-Aug-85	4.7	1.3	2.6	1.3	1.1	1.2	2.4	1.5
11-Aug-87	1.9	2.4	1.3	1.0	0.7	1.7	0.9	1.1
16-Aug-89	2.8	1.4	2.4	1.2	0.3	2.1	0.3	1.1

* Samples collected before tilling

Table 7 **Subsurface TPH Values (%) - 1982 Backshore Experiments**

	IMC				IME			
	Control		Mixed		Control		Mixed	
DATE	Berm	Back beach	Berm	Back beach	Berm	Back beach	Berm	Back beach
14-Aug-82*	0.2	0.0	0.7	0.0	1.5	0.0	1.8	0.0
15-Aug-82	0.1	0.1	0.0	0.8	1.1	0.0	1.3	1.2
22-Aug-82	0.2	0.0	2.7	0.9	0.1	0.0	0.8	1.5
15-Sep-82	0.7	0.1	2.3	0.8	1.3	0.3	1.2	1.5
20-Aug-83	0.1	0.0	0.2	0.5	0.7	0.7	0.8	0.6
10-Aug-85	1.0	0.0	0.6	0.2	1.2	1.2	0.9	0.7
11-Aug-87	2.0	0.1	1.4	0.6	0.7	0.7	0.8	0.7
16-Aug-89	0.5	0.2	0.4	0.1	0.4	0.4	0.8	0.1

*Samples collected before tilling

Table 8 **Weathering Ratios of Surface Samples - 1982 Backshore Experiments**

	IMC						IME					
	Control			Mixed			Control			Mixed		
YEAR/ LOCATION	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR
15-Aug-82 / Backbeach	2.0	2.6	2.8	2.6	2.5	NA	2.3	2.6	NA	2.3	2.6	2.4
22-Aug-82/ Berm	2.2	2.7	2.0	2.0	2.7	NA	2.0	2.6	NA	1.8	2.9	2.1
1983/ Backbeach	1.4	1.9	1.7	1.7	2.2	NA	1.6	2.4	NA	1.5	1.4	1.8
1983/ Berm	1.5	2.2	2.3	1.6	2.3	NA	1.7	2.3	NA	1.7	2.1	2.8
1985/ Backbeach	1.6	1.7	1.5	1.8	2.0	3.0	1.6	2.4	2.3	1.6	2.3	2.6
1987/ Backbeach	1.3	0.8	1.2	1.5	2.8	1.6	1.4	1.2	1.7	1.4	2.3	1.4
1989/ Backbeach	1.6	1.8	6.4	1.5	1.7	6.2	NA	NA	NA	NA	NA	NA

Table 9 Weathering Ratios of Subsurface Samples - 1982 Backshore Experiments

YEAR/ LOCATION	IMC						IME					
	Control			Mixed			Control			Mixed		
	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR	SHWR	ALK/ ISO	AWR
15-Aug-82/ Backbeach	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
22-Aug-82/ Berm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1983/ Backbeach	1.9	2.1	3.1	2.0	2.1	NA	2.1	2.3	NA	1.6	2.0	NA
1983/ Berm	2.4	2.3	NA	2.1	2.3	NA	2.0	2.2	NA	2.0	2.3	2.0
1985/ Backbeach	1.5	1.5	1.9	1.8	2.0	2.3	2.3	2.4	3.8	2.3	2.4	3.7
1987/ Backbeach	1.4	2.3	366	2.3	2.7	3.1	1.7	1.5	54	1.7	2.7	2.4
1989/ Backbeach	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

individual compound concentrations become very low.

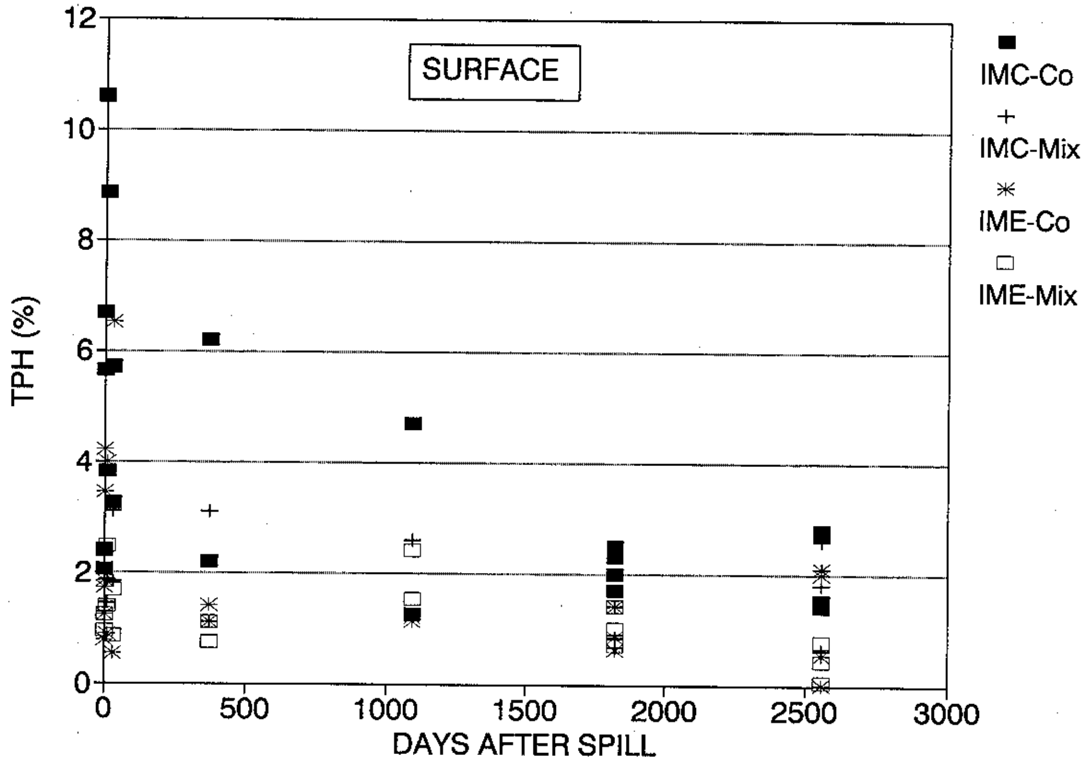
The weathering ratios of samples from these plots are similar to those from the 1980 backshore plots. In summary, there was an indication of evaporative weathering after the first year of exposure, with little evidence of any other type of weathering.

5.3 Discussion

In the backshore plots, the mixing of the oil appears to have slowed oil removal. Both control plots lost oil more rapidly than mixed plots, and the concentrations of subsurface oil were stable. Small changes in TPH were observed on the control plots in the first year only, with the mixed oil showing no change over the period of the experiment (Table 10). It appears that only

Table 10 Regression Analysis - 1982 Backshore Experiments

	Rate of change (%TPH per annum)	
	Surface	Subsurface
IMC-Co	0.4	<0.1
IMC-M	<0.1	0.1
IME-Co	0.2	<0.1
IME-M	<0.1	<0.1



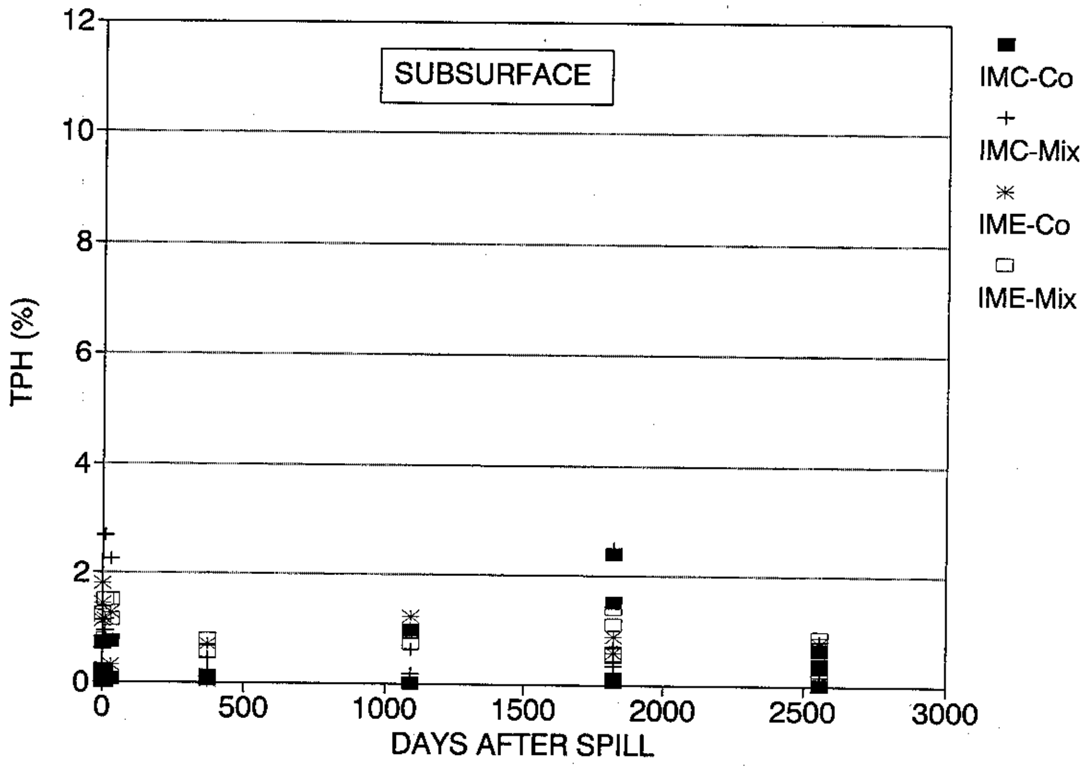


Figure 4 TPH Values (%) - 1982 Backshore Control Plots

fully exposed oil weathers. This is consistent with other plots, in that subsurface oil does not decline in concentration. Mixing increases the surface area of oil cover but shelters that oil from weathering processes at the beach surface. As the surface concentration is reduced, the net effect of mixing is to slow the natural removal of this type of oil from the backshore. Mixing would be more useful in exposing subsurface oil after the surface oil has been degraded or removed.

Results from the Bay 11 Intertidal Beach

6.1 Surface Oil Distribution

Visual observations on surface oil cover have been made in a systematic manner each year. These results have been used to prepare a series of maps showing the distribution of surface oil. In Figure 5, those distributions are shown from the week after the spill to August, 1989.

The total area of each coverage category was also determined from the visual observations. From 1981 to 1989, the area of the beach within which an oil cover was observed decreased to less than 20% of the original observed area (Table 11). A measure of the change in the degree or magnitude of the contamination is given by the Equivalent Oiled Area (EA) value which decreased by 87% over the period (Table 12).

6.2 Total Petroleum Hydrocarbons(TPH)

The analyses of the repetitive samples collected from the intertidal beach surface sediments show a general decrease in average surface TPH concentrations through time, and usually higher concentrations in samples from the upper and middle intertidal zones than in the lower intertidal zone sample (Table 13). The results from the repetitive samples of subsurface sediment show no trends either in time or space. The values are generally one or two orders of magnitude lower than those for the surface samples, although this is not universally applicable (Table 14).

There was considerable heterogeneity in the TPH values from the sediment samples. The graphs of the TPH concentrations over time, plotted by beach stratum, show how variable these results were (Figure 6). This large variance forces the regression analysis to indicate no change in concentration with time. Plotting the results by cross-beach transect over time (Figure 7) suggests that the initial oiling was not homogeneous, with heavier oiling at the south end of the beach (Transect 6) and lighter oiling at the north end (Transect 2). This description is not consistent with the visual observations recorded on the surface oil cover maps.

Sediment samples were also collected on a subjective (ad hoc) basis to reflect observed differences in the surface oil cover that corresponded to morphological beach features. These data (Table 15) indicate that the highest TPH concentrations were associated with the beach-face asphalt pavement (the range of values for the six pavement samples was 1.2 to 2.5%), with a secondary concentration of high values on the surface of the lower beach ridge pavement until 1989.

6.3 Oil Volume

In 1989, the computed volume of oil remaining in the surface sediments of the beach was about one-tenth of the initial volume of oil that was stranded in 1981, with minor differences depending on calculation method (Table 16).

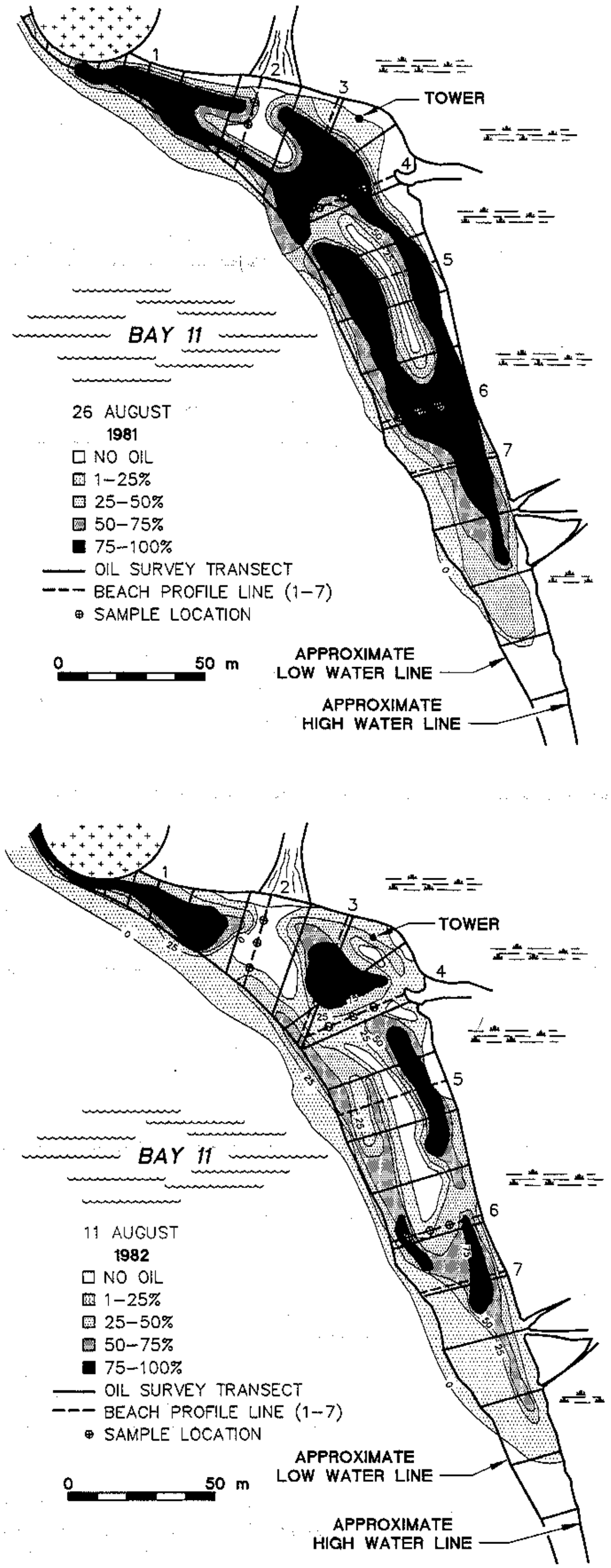


Figure 5 Intertidal Surface Oil Cover - Bay 11

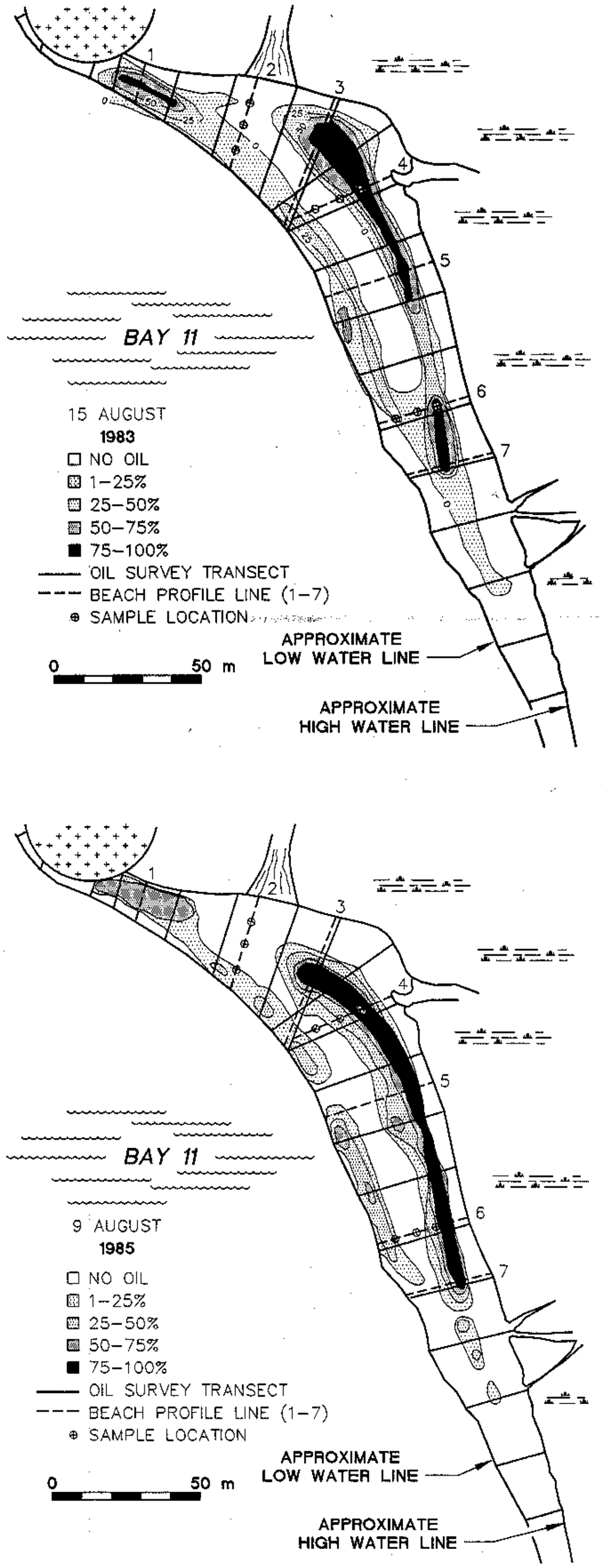


Figure 5 **Intertidal Surface Oil Cover - Bay 11 (Cont.)**

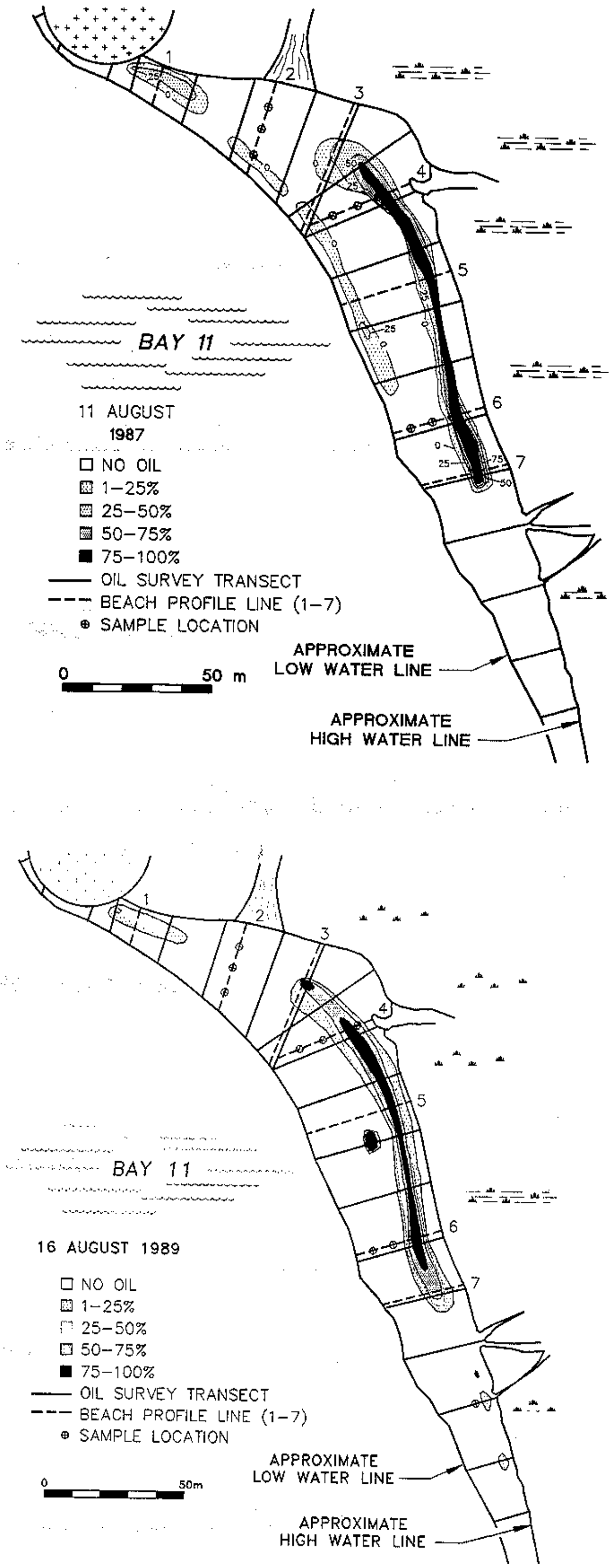


Figure 5 Intertidal Surface Oil Cover - Bay 11 (Cont.)

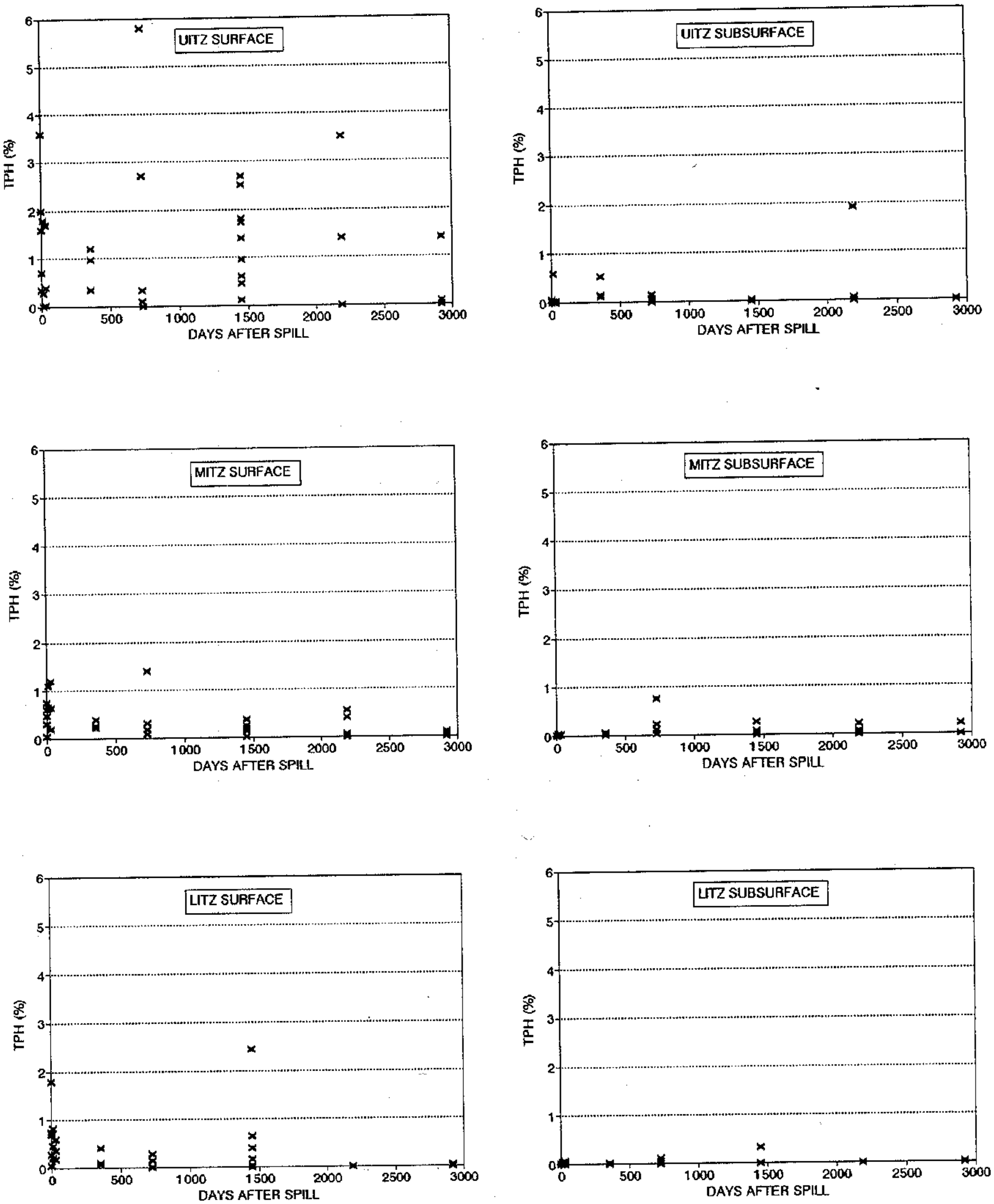


Figure 6 **Intertidal TPH Values (%) - Strata - Bay 11**

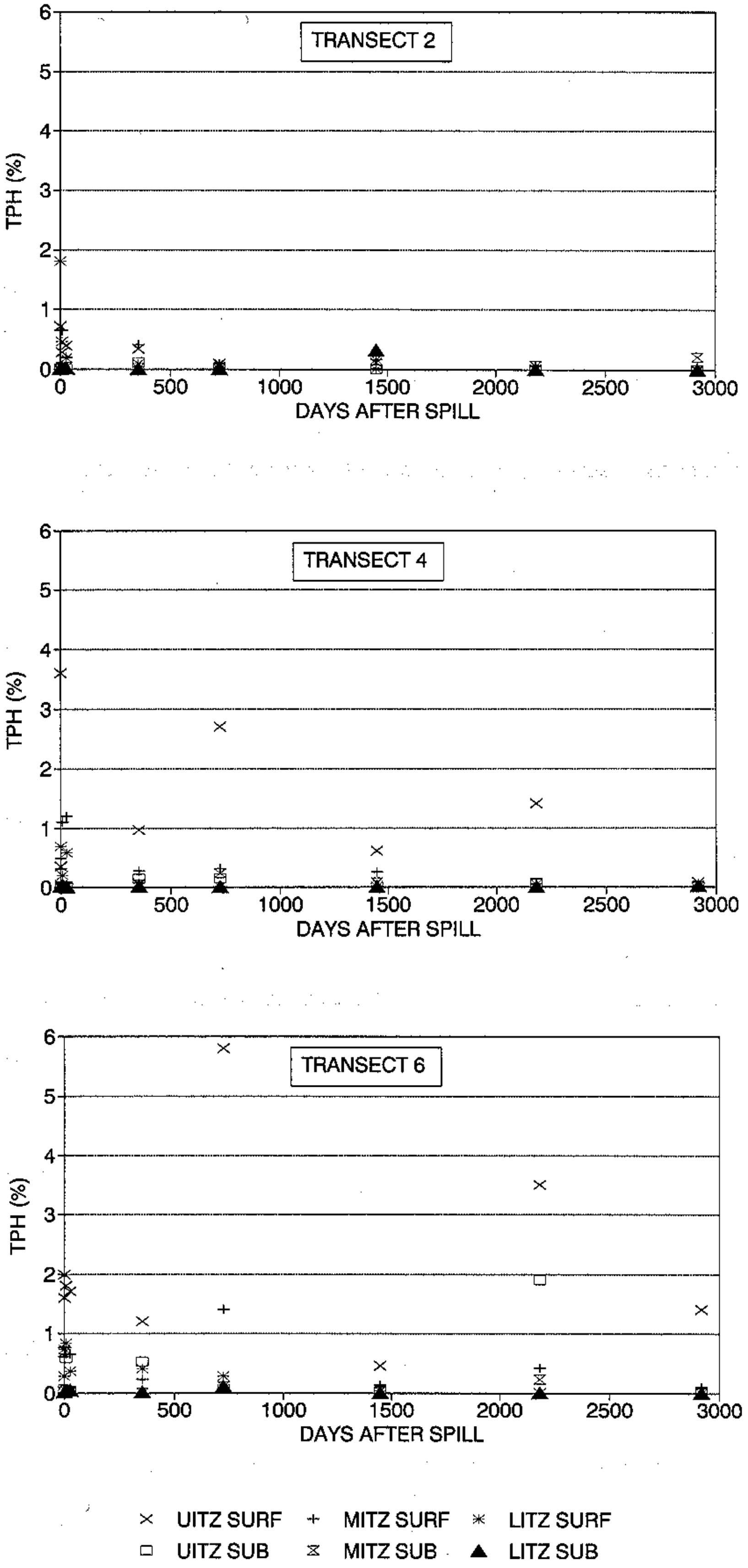


Figure 7 **Intertidal TPH Values(%) - Transects - Bay 11**

Table 11 Surface Oil Distribution

Year	Surface Oil Cover by Category (m2)					Total Oiled Area (m^{2}8)
	0%	0.1 to 24%	25 to 49%	50 to 74%	75 to 100%	
1981	6 200	2 015	1 700	1 145	3 710	8 570
1982	5 170	5 200	1 775	1 320	1 305	9 600
1983	10 845	2 120	840	350	615	3 925
1985	10 330	1 830	1 440	660	510	4 440
1987	12 530	1 040	560	280	360	2 240
1989	13 170	720	26	240	380	1 600
1981 to 1989	112%	-64%	-98%	-79%	-90%	-81%

Table 12 Changes in Estimated Oil Content of the Beach

YEAR	Total oiled area (m^2)	Equivalent area of 100% oil cover (m^2)	Average surface oil cover (%)	Percentage of beach area oiled
1981	8 570	4 850	57	58
1982	9 600	3 282	34	65
1983	3 925	1 337	34	25
1985	4 440	1 200	27	30
1987	2 240	800	36	15
1989	1 600	631	41	10

Table 13 Intertidal Surface TPH Mean Values (%) - Bay 11

DATE	Upper intertidal zone (UITZ)	Middle intertidal zone (MITZ)	Lower intertidal zone (LITZ)	Overall mean
19-Aug-81	2.8	1.9	0.5	1.7
20-Aug-81	0.9	0.4	0.9	0.7
28-Aug-81	0.7	0.8	0.5	0.7
15-Sep-81	0.7	0.7	0.4	0.6
10-Aug-82	0.8	0.3	0.2	0.4
16-Aug-83	2.9	0.6	0.1	1.2
09-Aug-85	0.4	0.1	0.06	0.2
12-Aug-87	1.6	0.2	<0.01	0.7
16-Aug-89	0.5	0.05	0.01	0.2
Regression 1981 to 1989 Annual change	<0.1%	<0.1%	<0.1%	

6.4 Weathering Ratios

Weathering ratios for samples from the Bay 11 intertidal beach are shown in Table 17. After the initial drop in values during the summer of 1981, the SHW ratios remained low, associated with the loss of the n-C10 to n-C17 saturated hydrocarbons by evaporation. Changes in the ALK/ISO ratios are similar, although in this case, the major reduction in the mean of the ratios, due to depletion of the n-alkanes by biodegradation, occurred between the September 1981 and August 1982 sample intervals.

A major distinction was found in the weathering ratios of samples with high (>0.5%) versus low (<0.5%) TPH concentration. As indicated by the SHWR, evaporative weathering was significantly lower in the high TPH samples. This pattern was also reflected in the ALK/ISO ratio and the AWR. The chromatograms for the samples with high TPH concentration are less weathered and include distinct, well-resolved alkanes, from about C10 up, and a low UCM (unresolved complex mixture). By contrast, the chromatograms from the low TPH concentration samples show much greater weathering and include a significant UCM and loss of alkanes relative to isoprenoids, although some alkanes can be resolved. Thus, weathering occurred at different rates depending upon the concentration of the oil in the sediments.

6.5 Asphalt Pavement

A major change in the character of the oil cover occurred with the formation of an asphalt pavement after the field survey in August 1982 and before the site visit in August 1983. Although relatively small in area (325 m^2 in 1983 and 205 m^2 in 1985), in 1983, the pavement contained approximately two-thirds of the oiled sediments on the beach and one-third in 1985. By 1987, the pavement had become more discontinuous than in previous years and it became difficult to estimate area and volume. Oil concentrations from pavement samples averaged approximately 2.0% in both 1983 and 1985, decreased to 1.6% in 1987, and the single 1989 sample had a TPH value of 1.4%. These samples showed relatively little weathering compared to non-pavement samples with low TPH concentrations. In all

Table 14 Intertidal Subsurface TPH Mean Values (%) - Bay 11

DATE	Upper intertidal zone (UITZ)	Middle intertidal zone (MITZ)	Lower intertidal zone (LITZ)	Overall mean
20-Aug-81	0.03	0.01	0.01	0.02
28-Aug-81	0.2	0.03	0.04	0.09
15-Sep-81	0.01	0.03	0.03	0.02
10-Aug-82	0.3	0.03	0.01	0.1
16-Aug-83	0.07	0.1	0.04	0.08
09-Aug-85	0.01	0.04	0.1	0.05
12-Aug-87	0.7	0.1	<0.1	0.3
16-Aug-89	0.01	0.07	0.01	0.03
Regression 1981 to 1989 Annual change	<0.1%	<0.1%	<0.1%	

Table 15 Ad-hoc Samples TPH Values (%) - Bay 11

		SURFACE		SUBSURFACE	
	YEAR	n	%	n	%
Beach Face (asphalt pavement)	1983	6	2.0	6	0.1
	1985	6	1.9	5	0.6
	1987	6	1.6	3	0.7
	1989	1	1.4	3	0.01
Mid-beach Trough	1983	3	0.05	3	<0.01
	1985	1	0.2	0	
	1987	3	0.3	0	
	1989	3	0.05	3	0.07
Lower Beach Ridge	1983	4	0.8	4	0.3
	1985	3	1.2	0	
	1987	6	0.5	0	
	1989	3	0.01	3	<0.01

Table 16 TPH (%) and Computed Oil Volume - Bay 11

DATE	Note	n	Mean surface TPH (%)	Surface oil volume (m^3)	
				EA	Computed
19-Aug-81	a	6	1.7	5.3*	5.3
20-Aug-81	a	9	0.7		2.2
28-Aug-81	a	9	0.7		2.0
15-Sep-81	a	9	0.6		1.8
10-Aug-82	a	9	0.4	3.6	1.5
16-Aug-83	a	9	1.2		1.6
	b	10	0.5		0.6
	c	19	0.8	1.5	1.1
09-Aug-85	a	9	0.2		
	b	14	1.2		
	c	23	0.8	1.3	1.3
12-Aug-87	a	8	0.7		
	b	21	0.6		
	c	29	0.6	0.9	0.5
16-Aug-89	d	3	0.5	0.7	0.3

* Initial 100% EA volume is assumed to be the same as the computed volume

Notes:
a: UITZ, MITZ, LITZ, Transects 2,4,6.
b: ad hoc samples.
c: a + b
d: UITZ only; visible oil samples only.

years, the samples from beneath the asphalt pavement had low TPH concentrations.

6.6 *Miscellaneous Samples*

A small number of samples of oil coated on rocks, with surface appearances varying from shiny to dull black, were collected and analyzed by GC/MS. All samples gave a similar distribution of hydrocarbons, and appeared to be weathered to the same degree as the asphalt pavement. Some pits were dug and samples were collected of the free oil that seeped onto the surface of the water that partially filled the pits. The oil appeared to be fresh and mobile. A sample was analyzed by GC/MS and the oil was relatively unweathered.

6.7 *Discussion*

6.7.1 *Surface Oil Cover*

A comparison of TPH results from the surface oil with the visual observations of surface oil cover forces the conclusion that TPH data acquired systematically with only a few sampling sites does not reflect actual oiling conditions. The maps of surface oil cover clearly show that the pre-determined sampling locations were in different oiled-beach features in different years. The variability observed for the more homogeneous backshore plots (T1/T2) is much higher in this more realistic intertidal spill situation. The number of samples required to statistically describe "the beach" is very high, of the order of one per square metre, or about 8 000 samples per year for Bay 11, based on the variance of the more homogeneous T1/T2 plots. This is clearly excessive for the value of the information generated. The TPH values of the surface samples, as determined in this project, do not provide any mechanism to predict future oil concentrations or to estimate trends.

The determinations of oil cover, length, area, and volume, provide different levels of confidence for different levels of effort. The summary of changes, as presented in Table 18 and Figure 8, indicates the trends determined in the Bay 11 situation. Oiled length, the easiest to determine, does not provide information regarding amount of oil. Area, determined as total oiled area, does not provide information regarding amount of oil, but is a better estimate than length. Equivalent Oiled Area (EA), based on an estimate of oil in a unit surface area, provides an index of oil concentration within each unit area. Longshore and across-shore variability, which may be associated with sediment type, beach geomorphology or

Table 17 Mean Weathering Indices - Bay 11

DATE	n	SHWR	ALK/ ISO	AWR
20-Aug-81	6	2.6	2.7	NA
15-Sep-81	6	1.6	2.6	NA
10-Aug-82	6	1.1	1.1	NA
16-Aug-83	6	1.4	1.3	NA
09-Aug-85	6	1.3	0.7	1.8
12-Aug-87	4	1	1.3	NA
16-Aug-89	10	1.2	0.05	1.3

Table 18 Summary of Changes - Bay 11

YEAR	Open water (months)	Length of oiled shore %	Total oiled area %	Equivalent oiled area %	Computed oil volume %
1981	0	100	100	100	100
1982	3	90	113	68	28
1983	5	70	45	28	21
1985	9	67	51	25	25
1987	13	58	26	16	9
1989	17	58	19	13	6

coastal processes, is integrated into a number representative of the whole beach. Oil volume depends on surface and subsurface TPH values, which are known to be a poor measure over a large (many hectares) area. Oiled sediment volume depends only on oil penetration data, and is probably a better estimate than oil volume, although it does not provide information on oil amount.

The data obtained indicate that the beach oiling is not consistent; the three transects monitored were different by both TPH and visual measurements. It is clear that full beach characterization must be based upon multi-transect surveys.

It is evident from Figure 8 that there was an initial period of change in oiled area and oil volume. Over the first five months, most of the stranded oil was removed by coastal (physical) processes. The rate of change over the next 12 months was much slower. It is expected that the reduction of oiled area and oil volume will continue at this slow rate unless an unusual event alters that rate. The beach has not been affected by storm waves or ice action over the study period, but either process could cause more change than the "normal" environmental conditions experienced to date. The rate of removal changed as the oil viscosity increased through time, as a result of weathering, and as the more accessible (surface) oil was removed. The oil that remains is weathered, sometimes tar-like, and predominantly within the surface sediments rather than on the surface of the beach.

6.7.2 Subsurface Oil

In general, the subsurface oil concentrations are much lower than the surface concentrations, but they depend on beach substrate composition. In the nearshore of Bay 11, the concentrations of subsurface oil at the monitoring locations were very much lower than the surface oil at the same site. The conclusion that surface TPH values do not describe the actual surface oil conditions on the beach must be extended to the subsurface TPH values as an indicator of subsurface oil conditions. Casual digging on the beach turned up oiled sediments and, occasionally, mobile oil.

The beach at Bay 11 is at the foot of a watershed, and during the summer, fresh water washes through the beach. This water carries oil with it, as seen in pits and by an occasional very light sheen spreading from the beach edge into the bay. Although minor, these observations indicate that there

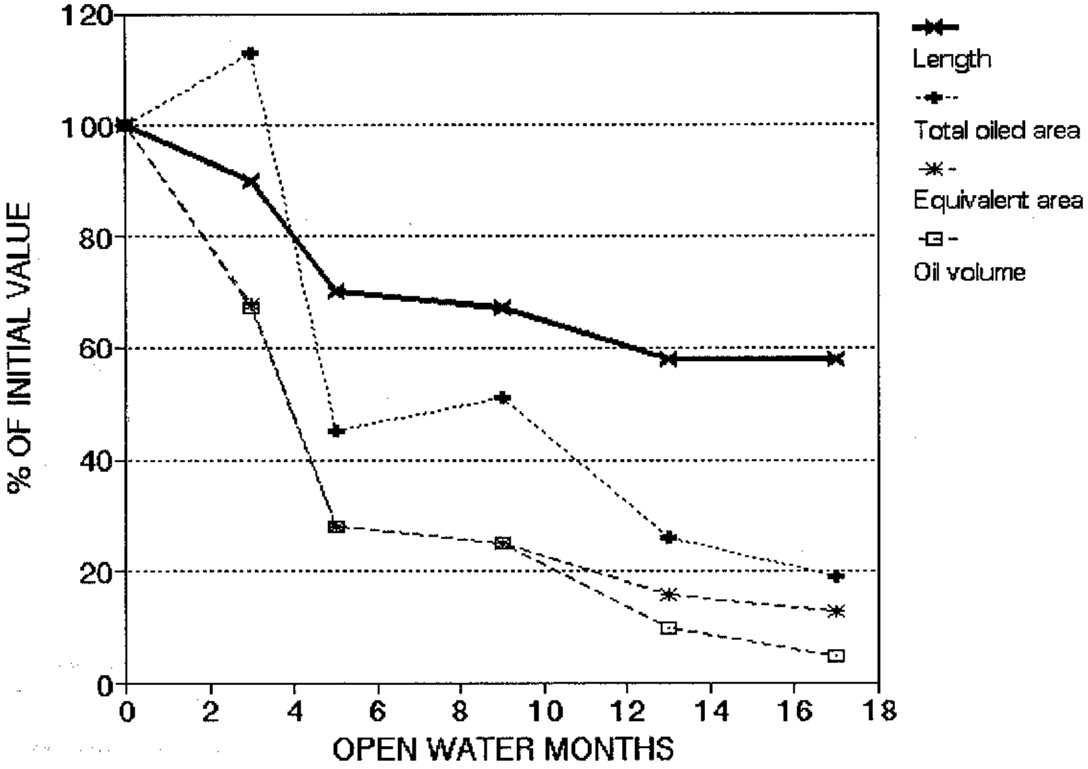


Figure 8 **Changes in Shoreline Surface Oil - Bay 11**

is oil hidden within the beach. Compositional analysis by GC/MS showed that the mobile oil was relatively fresh, as would be expected.

It is well accepted that coarse beach material permits more oil penetration than does fine material. Accurate determinations of particle size were not done. Given the small number of continuous sampling locations, such determinations would only have further confused the issue by introducing another parameter into a small data set. The results as they stand are not consistent with conventional wisdom that more oil penetrates in the upper intertidal zone than in the lower intertidal zone. This may be masked by other parameters not measured here.

Conclusions

The Baffin Island Oil Spill Project and subsequent monitoring program provide a consistent long-term record of oil stranded on arctic beaches. It is one of the few data base records that is appropriate for predicting the fate and persistence of stranded oil on coarse sediment shorelines in cold water environments. The following are the general conclusions from the programs.

In a typical oil spill scenario, natural environmental processes removed significant quantities of surface oil stranded on a sheltered beach. Although total removal was slow in terms of absolute time, it was rapid in terms of open-water (ice-free) time when self-cleaning processes can operate, and also considering the low wave energy levels at this site. After eight years or 17 open-water months, 90 to 95% of the surface contamination was gone. The combination of low wave energy and oil loading represent a worst-case scenario for a single oiling on a low permeability beach in a cold climate.

The natural removal rate of surface oil stranded in the intertidal zone was initially rapid, but the rate of change slowed significantly with subsequent reductions in the amount of free, unweathered oil. Most of the physical removal and weathering of stranded surface oil occurred in the first two years. Oiled area and oil volume decreased to 30% of the original estimates by the fifth open-water month, averaging more than 10% reduction per open-water month. Removal continued thereafter, with 5 to 10% of the original oil remaining on the surface after eight years, but the rates of change slowed dramatically, to approximately 1% per open-water month.

After two years, a major portion of the residual intertidal oil was contained in an asphalt pavement formation. High in the intertidal zone of Bay 11, a band of asphalt pavement formed after year two and was still present in the eighth year. This formation contained about 40% of the oil in the third year and about 53% in the eighth year. Asphalt pavements are common in real spill situations and are resistant to natural removal processes. They have been observed after the *Arrow, Metula, Amoco Cadiz, Exxon Valdez* and other cold water spills.

After eight years, the residual intertidal oil varied in physico-chemical characteristics, from a relatively fresh form to a highly weathered form. Generally, the surface oil residues were highly weathered, having been exposed to the air. Much of the oiled beach sediments had been worked and exposed by physical action. Weathering occurred at different rates depending on oil concentrations in the sediments, with lower TPH concentrations associated with greater weathering. Samples of asphalt pavement showed relatively little weathering compared to non-pavement samples with low TPH. Subsurface samples remained relatively fresh.

Subsurface oil behaviour is still not well understood. It continues to be of concern, however, with respect to long-term persistence and cleanup of oil. Monitoring of subsurface oil behaviour in this program was minimal. Fresh and mobile subsurface oil was found by digging pits eight years after the spill, but the extent and degree of oiling could not be estimated by visual or practical means. The original and current ratio of surface to subsurface oil is therefore unknown. In fact, the state of the art of subsurface oil monitoring is extremely poor. Nevertheless, observations from this and other spills indicate that subsurface oil is naturally removed and weathered at a much lower rate than surface oil. In some circumstances, this could lead to a longer-term concern and source of continued contamination.

The Equivalent Oiled Area (EA) method appears to be the most practical index for describing shoreline oiling and comparing temporal changes over the short to medium term. There are a number of commonly used indices with specific applications and uses. All have limitations. For example, length, width, and total oiled area do not capture the multidimensional, non-homogeneous distribution of oil. Likewise, both oil penetration and oil concentration data are very difficult to obtain accurately, and these dramatically affect any attempt to calculate volumetric values.

Total petroleum hydrocarbon(TPH) determinations obtained from coarse-grained sediments cannot be used alone to describe the beach, but may be used to describe specific features of the beach. The variances observed in the homogeneous plots (T1/T2) and the obvious disagreement of the Bay 11 TPH results with visual observations indicate that TPH determinations used in this project do not statistically describe the plots or beaches to any significantly useful level, but can be used to describe specific beach features. Only order of magnitude changes can be accepted from the data as collected. On coarse or mixed sediment beaches, it is likely that no acceptable level of sampling could provide adequate statistical confidence.Therefore, TPH measurements cannot be solely relied upon to characterize beach oiling conditions in these environments.

The natural removal of oil stranded in the backshore is a relatively slow process. It occurs when oil is fresh and exposed to the air, assuming no other forces apply. Surface oil located in the backshore, remote from marine influence and subject to sub-zero temperatures for nine months each year, evaporated during the first year of exposure. After that, however, the process was immeasurably slow, leaving about half the oil in place. Subsurface oil concentrations were essentially stable throughout the experiment. The implications are that oil which is not subject to dynamic environmental processes will persist for a very long period of time.

Tilling of fresh surface oil located in the backshore tended to reduce the net rate of removal. Natural evaporative loss was precluded when fresh surface oil was tilled into the subsurface sediments. Conversely, if subsurface oil was brought to the surface by tilling when relatively fresh, evaporative loss would proceed.

References

Boehm, P.D., "Chemistry 2: Hydrocarbon Chemistry - 1980 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 80-2, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 184 p. (1981)

Boehm, P.D., "Chemistry 2: Analytical Biochemistry - 1982 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 82-2, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 210 p. (1983)

Boehm, P.D., D.L. Fiest, and A. Elskus, "Comparative Weathering Patterns of Hydrocarbons from the 'Amoco Cadiz' Oil Spill Observed at a Variety of Coastal Environments", In: Proceedings of the International Symposium, 'Amoco Cadiz' Fates and Effects of the Oil Spill, Centre Oceanologique de Bretagne, Brest (France), p. 159-173 (1981)

Boehm, P.D., D.L. Fiest, and P. Hirtzer, "Chemistry 2: Analytical Biogeochemistry - 1981 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 81-2, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 354 p. (1982)

Boehm, P.D., W. Steinhauer, D. Cobb, S. Duffy, and J. Brown, "Chemistry 2: Analytical Biogeochemistry - 1983 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 83-2, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 139 p. (1984)

Boehm, P.D., M.S. Steinhauer, D.R. Green, B. Fowler, B. Humphrey, D.L. Fiest, and W.S. Cretney, "Comparative Fate of Chemically Dispersed and Beached Crude Oil in Subtidal Sediments of the Arctic Nearshore", *Arctic, 40* (Supplement 1): 133-148 (1987)

Brown, D.W., L.S. Ramos, A.J. Friedman, and W.D. MacLeod, "Analysis of Trace Levels of Petroleum Hydrocarbons in Marine Sediments Using a Solvent/Slurry Extraction Procedure", In: Trace Organic Analysis: A New Frontier in Analytical Chemistry, National Bureau of Standards, Special Publication Number 519, p. 161-167 (1979)

Buckley, J.R., B.R. de Lange Boom, and E.M. Reimer, "The Physical Oceanography of the Cape Hatt Region, Eclipse Sound, N.W.T.", *Arctic, 40* (Supplement 1): 20-33 (1987)

Bunch, J.N. and T. Cartier, "Microbiology 1: Effects of Petroleum Releases on the Microheterotrophic Flora of Arctic Sediments - 1983 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 83-5, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 44p. (1984)

Cross, W.E. and D.H. Thomson,"Effects of Experimental Releases of Oil and Dispersed Oil on Arctic Nearshore

Macrobenthos. I. Infauna", *Arctic, 40* (Supplement 1): 184-200 (1987)

Cross, W.E., C.M. Martin, and D.H. Thomson, "Effects of Experimental Releases of Oil and Dispersed Oil on Arctic Nearshore Macrobenthos. II. Epibenthos", *Arctic, 40* (Supplement 1): 201-210 (1987a)

Cross, W.E., R.T. Wilce, and M.F. Fabijan, "Effects of Experimental Releases of Oil and Dispersed Oil on Arctic Nearshore Macrobenthos. III. Macroalgae", *Arctic, 40* (Supplement 1): 211-219 (1987b)

Dickins, D.F., "Ice Conditions at Cape Hatt, Baffin Island", *Arctic, 40* (Supplement 1): 34-41 (1987)

Dickins, D.F., D.E. Thornton, and W.J. Cretney, "Design and Operation of Oil Discharge Systems and Characteristics of Oil Used in the Baffin Island Spill Project, *Arctic, 40* (Supplement 1): 100-108 (1987)

Eimhjellen, K. and K. Josefson, "Microbiology 2: Biodegradation of Stranded Oil - 1983 Results", Baffin Island Oil Spill (BIOS) Project Working Report 83-6; Environmental Protection Service, Environment Canada, Edmonton, Alberta, 58 p. (1984)

Emery, K.O., "A Simple Method of Measuring Beach Profiles", *Limnology and Oceanography, 6:* 90-93 (1961)

Green, D.R.,"Chemistry 1: Field Sampling and Environmental Chemistry - 1980 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 80-1, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 93 p. (1981)

Green, D.R., B. Humphrey, and B. Fowler, "Chemistry 1: Field Sampling and Total Hydrocarbon Analysis - 1981 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 81-1, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 111 p. (1982)

Hope, D. and B. Humphrey, "Long-term Fate and Persistence of Stranded Oil at Cape Hatt, N.W.T., and from the 'Amoco Cadiz' Spill - Part III. Environment Canada, Unpublished Report No. EE-84, River Road Technology Centre, Ottawa, 11 p. (1986)

Humphrey, B., "Chemistry 1: Field Sampling and Measurements - 1982 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 82-1, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 64 p. (1983)

Humphrey, B., "Chemistry l: Field Sampling and Measurements - 1983 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 83-l, Environmental Protection Services, Environment Canada, Edmonton, Alberta, 64 p. (1984)

Humphrey, B., P.D. Boehm, M.C. Hamilton, and R.J. Norstrom, "The Fate of Chemically Dispersed and Untreated Crude Oil in Arctic Benthic Biota", *Arctic, 40* (Supplement 1): 149-161 (1987a)

Humphrey, B., D.R. Green, B.R. Fowler, D. Hope, and P.D. Boehm, "The Fate of Oil in the Water Column Following Experimental Oil Spills in the Arctic Marine Nearshore", *Arctic, 40* (Supplement 1): 124-132 (1987b)

Humphrey, B., G.A. Sergy, and E.H. Owens, "Stranded Oil Persistence in Cold Climates", Proceedings of the 13th Arctic Marine Oil Spill Program Technical Seminar, June 6-8. Edmonton, Alberta. p. 401-410 (1990)

Humphrey, B., E.H. Owens, and G. Sergy, "Long-term Results from the BIOS Shoreline Experiment - Surface Oil Cover", Proceedings of the International Oil Spill Conference, San Diego, March 4-7, p. 447-452 (1991)

Meeres, L.S., "Meteorological Studies at Cape Hatt, N.W.T. in Support of the BIOS Project", *Arctic, 40* (Supplement 1): 42-50 (1987)

Owens, E. H., "Shoreline Countermeasures - 1983 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 83-4, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 102 p. (1984a)

Owens, E. H., "Variability in Estimates of Oil Contamination in the Intertidal Zone on a Gravel Beach", *Marine Pollution Bulletin, 15*(11): 412-416 (1984b)

Owens, E.H., "Estimating and Quantifying Oil Contamination on the Shoreline", *Marine Pollution Bulletin, 18*(3) 110-118 (1987)

Owens, E.H. and J.R. Harper, "Frost Table and Thaw Depth in the Littoral Zone near Peard Bay, Alaska", *Arctic, 30*: 154-168 (1977)

Owens, E.H. and W. Robson, "The 'Amoco Cadiz' Incident: Site Visits Seven Years After the Spill", Environment Canada, Unpublished Report No. EE-63, River Road Technology Centre, Ottawa, 34 p. (1985)

Owens, E.H. and W. Robson, "Field Observations of Stranded Oil in the Strait of Magellan Chile, 12 Years After the 'Metula' Spill", Environment Canada, Unpublished Report No. EE-89, River Road Technology Centre, Ottawa, (1987a)

Owens, E.H. and W. Robson, "Experimental Design and the Retention of Oil on Arctic Test Beaches", *Arctic, 40* (Supplement 1): 230-243 (1987b)

Owens, E.H. and B. Humphrey, "Long-term Fate and Persistence of Stranded Oil from the BIOS Project, N.W.T., Canada and from the Metula Spill, Tierra del Fuego, Chile, 1987 Results", Unpublished Report to Environment Canada, Edmonton, Alberta. 109 p. (1988)

Owens, E.H., J.R. Harper, and C.R. Foget, "Shoreline Countermeasures - 1981 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 81-4. Environmental Protection Service, Environment Canada, Edmonton, Alberta, 123 p. (1982)

Owens, E.H., J.R. Harper, and C.R. Foget, "Shoreline Countermeasures - 1982 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 82-4, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 129 p. (1983)

Owens, E.H., D. Hope, and B. Humphrey, "Long-term Fate and Persistence of Stranded Oil at Cape Hatt, N.W.T., and from the 'Amoco Cadiz' Spill - Part I, Cape Hatt Shoreline Study", Environment Canada, Unpublished Report No. EE-84, River Road Technology Centre, Ottawa, 98 p. (1986a)

Owens, E.H., W. Robson and B. Humphrey, "Data on the Character of Asphalt Pavements", Proceedings of the Ninth Arctic Marine Oil Spill Program (AMOP) Technical Seminar, June 10-12, Edmonton, Alberta, 1-17 (1986b)

Owens, E.H., J.R. Harper, W. Robson, and P.D. Boehm., "Fate and Persistence of Crude Oil Stranded on a Sheltered Beach", *Arctic, 40* (Supplement 1): 109-123 (1987a)

Owens, E.H., W. Robson, B. Humphrey, D. Hope, and J.R. Harper, "The Fate of Stranded Oil Four Years After an Experimental Spill on a Sheltered Gravel Beach", Proceedings, 1987 Oil Spill Conference, April, Baltimore, MD, American Petroleum Institute, Washington, D.C., Pub. No. 4452, 473-482 (1987b)

Owens, E.H., G.A. Sergy, and B. Humphrey, "The Migration of Stranded Oil From a Sheltered Beach into Adjacent Nearshore Subtidal Sediments", In: Fate and Effects of Oil in Marine Ecosystems, J. Kuiper and W.J. Van den Brink, Eds., Martinus Nijhoff Publishers BV, Dordrecht, The Netherlands, 231-241 (1987c)

Owens, E.H., W. Robson, and C.R. Foget, "A Field Evaluation of Selected Beach Cleaning Techniques", *Arctic, 40* (Supplement 1): 244-257 (1987d)

Owens, E.H., W. Robson and B. Humphrey, "Observations from the 'Metula' Spill 12 Years After the Incident", Proceedings of the 10th Arctic Marine Oil Spill Program (AMOP) Technical Seminar, June 9-11, Edmonton, Alberta (1987e)

Sergy, G.A. and P.J. Blackall, "Designs and Conclusions of the Baffin Island Oil Spill Project", *Arctic, 40* (Supplement 1): 1-9 (1987)

Sergy, G.A., B. Humphrey, and E.H. Owens, "On Describing and Estimating the Fate of Stranded Oil", Proceedings of the International Oil Spill Conference, San Diego, March 4-7, p. 489-492 (1991)

Woodward-Clyde Consultants, "Shoreline Countermeasure - 1980 Study Results", Baffin Island Oil Spill (BIOS) Project Working Report, 80-4, Environmental Protection Service, Environment Canada, Edmonton, Alberta, 83 p. (1981)

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