ARCTIC
VOL. 40, SUPP. 1 (1987) P. 109-123

Fate and Persistence of Crude Oil Stranded on a Sheltered Beach

EDWARD H. OWENS,[1] JOHN R. HARPER,[2] WISHART ROBSON[3] and PAUL D. BOEHM[4]

(Received 12 June 1986; accepted in revised form 9 February 1987)

ABSTRACT. Detailed observations, mapping and sampling were conducted following an experimental spill of 15 m^3 of crude oil adjacent to the coast at Cape Hatt, Baffin Island, N.W.T. The beach could not retain all of the oil that reached the shoreline, and as a result, one-third of the spilled oil was recovered in cleanup activities on the water, approximately one-third was lost to the atmosphere and to the ocean and one-third remained stranded on the intertidal zone. The stranded oil was subject to natural cleaning processes during approximately 6 months of open-water periods from 1981 to 1983. Over this period the surface area of oil cover was reduced by approximately half, whereas estimates indicate that 80% of the oil initially stranded (5.3 m^3) was removed. This natural removal of stranded oil occurred in a very sheltered environment. The reduction of the surface area and of the volume of oil resulted primarily from the physical processes associated with wave activity and ground-water leaching. By 1983 an asphalt pavement had developed in the upper intertidal zone on the beach-face slope. Total hydrocarbon concentrations of samples collected from the asphalt pavement indicated a significant increase in oil-in-sediment values in this zone to concentrations in the order of 2-5%. Oil removed from the beach was transported into the adjacent nearshore bottom sediments, where oil concentrations increased sixfold between 1981 and 1983. Physio-chemical weathering rates were relatively rapid immediately following the release of the oil, as the lower molecular weight (C_1 to C_{10}) hydrocarbons evaporated. Subsequent physio-chemical changes were heterogeneous: weathering and biodegradation progressing slowly where oil-in-sediment concentrations exceeded 1%. The primary conclusion from the investigations undertaken to date is that oil is removed in substantial quantities from the intertidal zone even in such a sheltered, low-energy arctic environment. Similar changes should also be expected from comparable environments in lower latitudes.

Key words: oil spill, natural oil weathering, asphalt pavement, beached oil

RÉSUMÉ. On a effectué des observations, des prises d'échantillons et des relevés détaillés à la suite d'un déversement expérimental de 15 m^3 de pétrole brut, à proximité de la côte du cap Hatt à l'île Baffin (T. N.-O.). La plage n'a pas pu retenir tout le pétrole qui a atteint le rivage, et il a fallu en enlever un tiers de la surface de l'eau lors d'opérations de nettoyage. Un autre tiers environ a été éliminé par évaporation et par dissolution dans l'océan, et le dernier tiers est resté échoué sur la laisse. Ce pétrole échoué a été soumis à des processus de nettoyage naturels pendant les périodes d'eau libre totalisant environ 6 mois entre 1981 et 1983. Pendant cette période, la surface couverte de pétrole a diminué environ de moitié, et on estime qu'environ 80% du volume original du pétrole échoué (5,3 m^3) a été éliminé. Cette élimination naturelle du pétrole échoué s'est produite dans un environnement très abrité. La diminution de la surface contaminée et du volume de pétrole était due principalement aux processus physiques reliés à l'action des vagues et au ruissellement de l'eau sur le sol. Une plaque d'asphalte s'était formée, avant 1983, dans la zone supérieure de la laisse, sur la partie inclinée de la plage. Des échantillons prélevés dans la plaque d'asphalte avaient des concentrations totales d'hydrocarbures qui indiquaient une augmentation significative de la quantité de pétrole dans les sédiments de cette zone, jusqu'à des concentrations de l'ordre de 2 à 5%. Le pétrole enlevé de la plage était transporté dans les sédiments du fond de la mer près du rivage, où les concentrations en pétrole ont été multipliées par six entre 1981 et 1983. La dégradation physio-chimique était relativement rapide juste après le déversement de pétrole, pendant l'évaporation des hydrocarbures de faible poids moléculaire (C_1 à C_{10}). Les changements physio-chimiques subséquents étaient hétérogènes, la dégradation et la bio-décomposition progressant lentement là où les concentrations de pétrole dans les sédiments dépassaient 1%. La conclusion principale des études entreprises jusqu'à présent est que, même dans un environnement arctique à faible énergie aussi abrité, le pétrole est éliminé de la laisse en quantités importantes. On s'attend à une évolution semblable dans des environnements situés à des latitudes plus basses.

Mots clés: déversement de pétrole, dégradation naturelle du pétrole, plaque d'asphalte, pétrole échoué

Traduit pour le journal par Nésida Loyer.

INTRODUCTION

The Baffin Island Oil Spill (BIOS) Project involved a series of related studies that investigated the fate and effects of untreated and treated oil spills in a northern marine environment. Sergy and Blackall (1987) provide an overall summary of rationale, design and results. One component of this multidisciplinary experiment had as its objective the short- and long-term monitoring of a nearshore release of 15 m^3 of aged Lagomedio crude oil allowed to drift ashore onto an adjacent gravel beach. The fate of the oil, in terms of concentrations and composition changes, was monitored in four major environmental components: the water column (Humphrey *et al.*, 1987b), the intertidal beach sediments (this paper), 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 and subtidal sediments (Eimhjellen and Josefson, 1984; Bunch and Cartier, 1984). As part of the shoreline studies, the distribution of surface oil was mapped and the beach sediments were sampled and analyzed for hydrocarbon concentrations and composition at intervals following the release of the oil. This data set was used to determine quantitative changes in the distribution of stranded oil and in the budget of oil on the shore. The objectives of this paper are to present a time-series set of results from the shoreline component of the experiment that (1) demonstrate the character of the chemical and physical changes in the stranded oil, (2) describe changes in the intertidal oil distribution and (3) estimate the changes in the volume of stranded oil. Additional data on related aspects of the shoreline phase of the BIOS Project are given by Owens and Robson (1987) and Owens *et al.* (1987c).

Previous studies have provided information on various aspects of the persistence and fate of stranded oil. The distribution of oil on the shoreline and natural self-cleaning have been described in detail following the *Arrow* spill (Owens, 1971; Owens and Rashid, 1976; Thomas, 1977), the *Amoco Cadiz* spill (Hayes *et al.*, 1979), the *Metula* spill (Blount, 1978; Gundlach *et al.*, 1982) and the IXTOC blowout (Gundlach *et al.*, 1981). Based

[1]Woodward-Clyde Consultants, 7330 Westview Drive, Houston, Texas 77055, U.S.A.
[2]CCOP/SOPAC: Mineral Resources, Private Mail Bag, GPO Suva, Fiji.
[3]Halliburton Manufacturing and Services Ltd., Ctra. Madrid-Barcelona, K.M. 15,300, Coslada (Madrid), Spain
[4]Battelle Ocean Sciences, 397 Washington Street, Duxbury, Massachusetts 02332, U.S.A.

in part on these field investigations, the processes that control the persistence of stranded oil in terms of the oil cover and of oil volumes have been discussed by numerous authors (e.g., Fusey and Oudot, 1984; Gundlach and Hayes, 1978; Gundlach *et al.*, 1985; Gundlach and Reed, 1986; Nummedal, 1979; Owens, 1978, 1985; Reed *et al.*, 1986; Tsouk *et al.*, 1985; Vandermeulen and Gordon, 1976; Vandermeulen, 1977, 1982). Analytical data on stranded oil weathering have been presented by Boehm *et al.* (1981), Calder *et al.* (1978), Calder and Boehm (1981), Cretney *et al.* (1978), Keizer *et al.* (1978), Rashid (1974) and Vandermeulen *et al.* (1977). These field studies and analyses of spilled oil have been in response to shoreline contamination following spill incidents. In the shoreline phase of the BIOS Project it was possible to collect data and samples on a preplanned design over a period of years from a small area of shoreline (10 000 m^2). The project has produced a time-series data set that considers the fate and weathering of stranded oil in greater detail than had been possible in previous studies.

The results presented in this paper are based upon a reinterpretation of the entire data set from the 1981 through 1983 field activities funded by the BIOS Project. This reinterpretation has resulted in an updating of the derived data sets presented in the BIOS Working Reports (Owens *et al.*, 1982, 1983; Owens, 1984a). The oil budgets and the surface oil distribution results and interpretations presented here represent a more accurate and thorough analysis than was possible in earlier unpublished documents. Subsequent data collected in 1985 as a follow-on study have been presented elsewhere (Owens, 1987; Owens *et al.*, 1986a,b, 1987a,b).

PHYSICAL SETTING

The location of the experiment, designated as Bay 11, is on the eastern shore of Ragged Channel, adjacent to Cape Hatt, on northern Baffin Island (Fig. 1). This site is a fiord coast and the fetch within the Ragged Channel fiord is less than 10 km. The beach is sheltered from the north and open to waves through a 60° arc between southwest and west-northwest. The open-water season in this area is on the average 65 days each year, but may vary from as little as 35 days up to a maximum of 90 days (Dickins, 1987). No long-term wind data for the region are available but observations indicate that the prevailing winds during the open-water season (July through October) are from the northwest quadrant (Meeres, 1987). This shoreline is subject to refracted waves from the northwest.

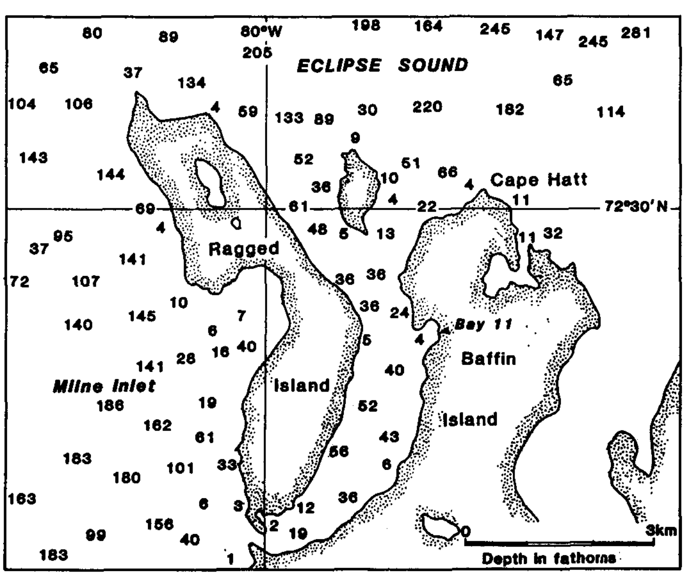

FIG. 1. Location of Bay 11 in Ragged Channel, Baffin Island, N.W.T. (water depths are shown in fathoms).

The tidal range at the study site varies between 1.0 m at neap tides and 2.0 m at spring tides. The tides are semi-diurnal and unequal in height, and the tidal range at the time of the experimental spill was 1.9 m (Buckley *et al.*, 1987).

The limits of the Bay 11 beach are set by two bedrock outcrops 400 m apart that shelve steeply (45°) into the water. The width of the intertidal zone of the beach varies throughout the bay and is greatest in the central part, with a maximum width of approximately 50 m. The lower intertidal zone is characterized by a low ridge that has the features of an ice-formed incipient boulder barricade. This ridge is composed predominantly of gravel- and cobble-sized sediments. The ridge gives way landward to a wide trough of silt and sand-sized sediments that is a pathway for freshwater streams to cross the beach from the backshore. Landward, the trough gives way to a beach-face slope of sand and gravel material, which terminates just above the mean high-water mark in the form of low pebble/cobble berms. The beach is subject to change by the redistribution of sediments by wave and ice action. Water within the sediments would be affected by the normal freeze and thaw processes associated with the movement of the frost table in the intertidal zone (Owens and Harper, 1977).

EXPERIMENTAL DESIGN AND METHODS

Oil Release

On 19 August 1981, approximately 15 m^3 of Lagomedio crude oil, which had been weathered artificially (8% loss by weight), was discharged onto the water surface adjacent to the shoreline of Bay 11 (Dickins *et al.*, 1987). The period of discharge (15:40-21:40 h) coincided with the ebbing tide. The 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 (see Fig. 3a). At the end of the discharge period (which was low tide), operations commenced to remove oil that had not stranded on the beach from the water surface by skimming and sorbants. Removal of oil from the water surface continued from the evening of 19 August to 16:00 on 21 August, when it was decided there was insufficient refloating of oil from the shoreline to continue operations. Four complete tidal cycles had elapsed by this time. A total of approximately 5.5 m^3 of oil was recovered. The booms were left in place for several weeks thereafter to contain sheening and redistribution of minor quantities of refloated oil.

Intertidal Oil Cover Surveys

The intertidal surface distribution of oil was mapped by a series of surveys conducted in 1981, 1982 and 1983. Each survey involved visual observations of the percentage of oil cover at a 2 m interval along 19 cross-beach profiles set 20 m apart, perpendicular to the low-water line. A single observation estimated the surface oil cover, to the nearest 5%, over an area of approximately 40 m^2. The observations made in 1983 used a slightly different technique, pacing rather than taping, but the comparison of these data with those from the previous years is nevertheless valid. Cross-checking by two independent observers in 1983 established the repeatability of the mapping technique to be on the order of ±5% (Owens, 1984b). These visual observations were used to calculate the Equivalent Area of 100% Oil Cover (100%EA). For example: 9 observations (equal to an area of 360 m^2) of a 10% oil cover yield a 100%EA value of 36 m^2, and 5 observations of 80% cover would give a value of 160 m^2. The 100%EA value for each complete data set is obtained by summation of the 21 individually calculated values. To simplify the presentation of the oil distribution data the observations have been grouped into four categories: light cover, 0.1-24%; light to moderate cover, 25-49%; moderate to heavy cover, 50-74%; and heavy cover, 75-100%.

In addition to these systematic surveys, visual estimates were made on each occasion from a helicopter flying at approximately 100 m elevation and from a rock outcrop at the northern end of the study beach, approximately 5 m above the high-water mark (Owens, 1984b).

Sediment Sampling and Chemistry Analyses

Sediment samples up to 2.4 *l* in size were collected from the surface (top 2 cm) and the subsurface (5-10 cm depth) of the intertidal beach. Samples were taken on three occasions in 1981 (one day, one week and three weeks after the release) and on one occasion in each of the 1982 and 1983 field surveys. A surface and a subsurface sample were collected along each of three beach profiles in 1981 and four profiles in 1982 and 1983 from the lower, middle and upper third of the intertidal zone (Owens *et al.*, 1982, 1983; Owens, 1984a). This sample set was intended to provide data on changes in the total hydrocarbon (t-h) content of the sediments through time. In 1983 additional samples were collected to provide data on specific features, in particular the asphalt pavement that had formed by that time.

The total hydrocarbon analysis by infra-red spectrophotometry consisted of a solvent extraction, using Freon 113, followed by measurement of a CH_2 absorption at 2850 cm^{-1}. The detection limit was 30 $mg \cdot kg^{-1}$, with a precision at low concentrations of 10 $mg \cdot kg^{-1}$ and of 1% at high concentrations. Sampling accuracy, the validity of the analytical results and the interpretation of the data are discussed by Humphrey (1984) and by Owens and Robson (1987).

Extraction, fractionation and analysis of the samples were based on the method of Brown *et al.* (1979). 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). Three diagnostic ratios were used to describe weathering (Table 1). Biodegradation is indicated by the Alkane-Isoprenoid Ratio (ALK/ISO), which approaches 0 as the *n*-alkanes are preferentially depleted. Evaporative weathering is indicated by the Saturated Hydrocarbon Weathering Ratio (SHWR), which approaches 1.0 as low-boiling-point saturated hydrocarbons (n-C_{10} to n-C_{17}) are lost by evaporation. The Aromatic Weathering Ratio (AWR) approaches 1.0 as low-boiling-point aromatics are lost by evaporation and/or dissolution (Boehm *et al.*, 1987).

Oil Budget Computations

Two methods were developed to calculate the volume of surface oil on the beach. The first is based on changes in the distribution of the surface oil cover, whereas 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 100%EA value. A change in the 100%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 100%EA value is reduced by half between two surveys, the volume of surface oil is assumed also to have halved over that same interval.

The second ("volume") method integrates the total hydrocarbon concentrations with the oil distribution data. The total area of the oiled beach, 8570 m^2 in August 1981, is multiplied by the sample depth of 2 cm to give a volume of the oiled beach surface at the time 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 metric tonnes or 274 000 kg. As the mean oil concentration is 17 400 $mg \cdot kg^{-1}$ on 19 August 1981, and as there are 274 000 kg of sediment, multiplication gives 4772 kg of oil on the beach on that date. Using a density of 890 $kg \cdot m^{-3}$ for the oil, this converts to a volume of 5.3 m^3 of oil on the beach surface on 19 August 1981.

TABLE 1. Petroleum weathering ratios

(a) The Biodegradation Ratio (Alkane/Isoprenoid)

$$\mathrm{ALK/ISO}_{14\text{-}18} = \frac{1400 + 1500 + 1600 + 1700 + 1800}{1380 + 1470 + 1650 + 1708 + 1810}$$

(b) The Saturated Hydrocarbon Weathering Ratio (SHWR)

$$\mathrm{SWHR} = \frac{\text{sum of } n\text{-alkanes from } n\text{-}C_{10} \text{ to } n\text{-}C_{25}}{\text{sum of } n\text{-alkanes from } n\text{-}C_{17} \text{ to } n\text{-}C_{25}}$$

(c) The Aromatic Weathering Ratio (AWR)

$$\mathrm{AWR} = \frac{\text{Alkyl benzenes + naphthalenes + fluorenes + phenanthrenes + dibenzothiophenes}}{\text{Total phenanthrenes + dibenzothiophenes}}$$

RESULTS AND OBSERVATIONS

Distribution of Oil on the Shore

Light southerly winds prevailed during the initial oiling period and resulted in heaviest loading levels on the northeast portion of the Bay 11 shoreline. Visually observed concentrations were highest along the high-water mark and on the ridge near the low water. The upper oil limit was visible as a distinct line, indicating that oiling occurred under very calm conditions. Observations showed that the oiling of beach sediments was variable and patchy and was most uneven along the southern part of the shoreline, where oiling was also the lightest. After a period of three days, oil apparently came in direct contact with mineral material and was much more resistant to refloating. Initially oiled rocks could be placed in a small stream at the site and cleaned within 10-15 min, but a few days later the same test resulted in very little oil being removed (D. MacKay, pers. comm. 1984). This was consistent with the observations of others that by the third day only minor quantities of oil were being refloated offshore by tidal action (G. Sergy, pers. comm. 1984) and is similar to events reported at the *Amoco Cadiz* incident (Hayes *et al.*, 1979).

On the evening of 25 August 1981, prior to the first oil distribution survey, a higher tide caused oiling above the

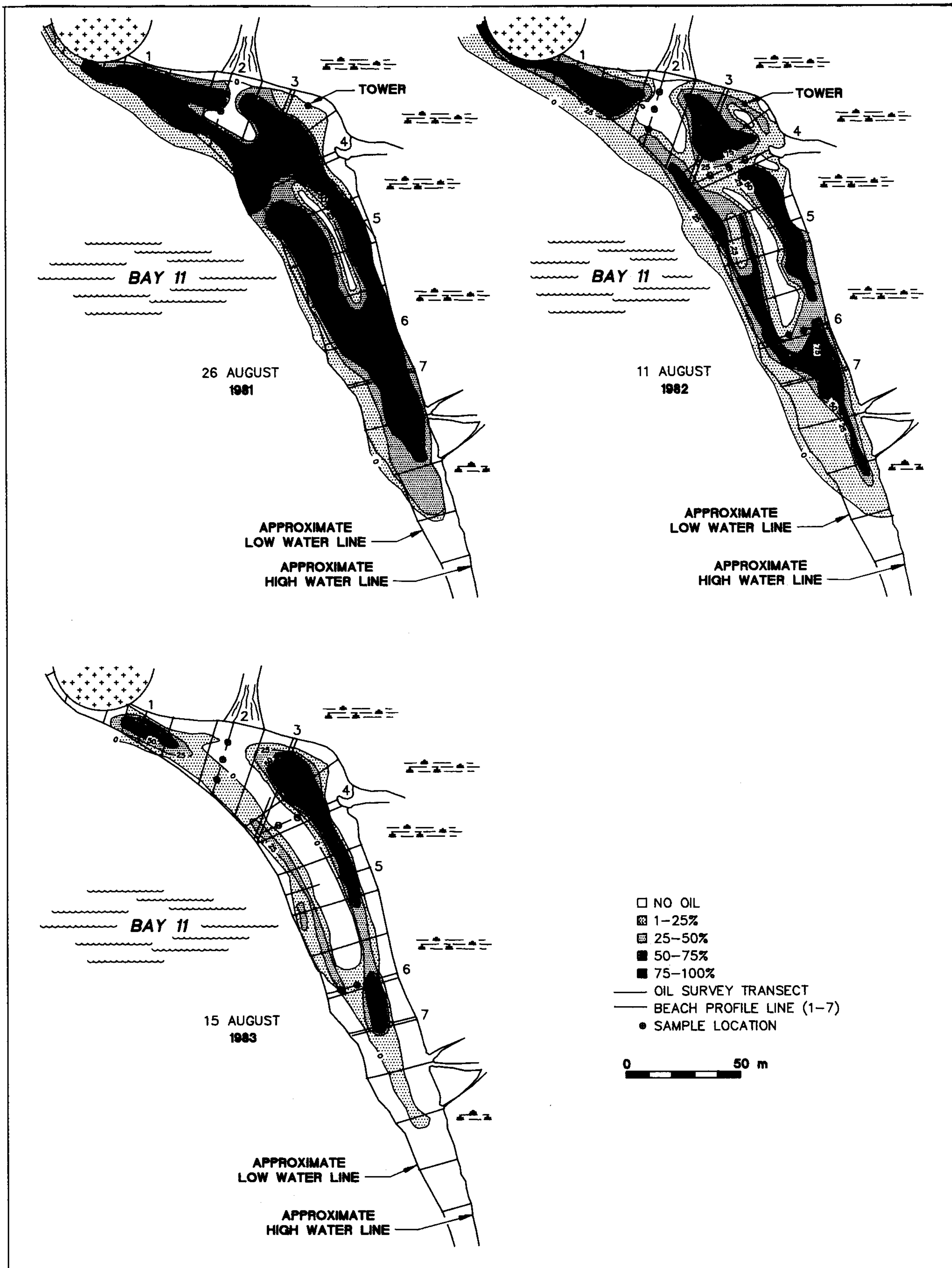

FIG. 2. Mapped surface oil distribution. Observations were made along the cross-beach transects (solid lines); beach profiles were surveyed along the dashed lines: (a) 26 August 1981; (b) 11 August 1982; (c) 15 August 1983.

previous upper oiling limit. It is significant that very little oil was redistributed, the initial oiling line remained distinct and oil coverings in the newly oiled areas were less than 10%. Temperatures were low during the high tide; frazil ice formed near the swash line and may have contributed to the lack of free oil available for contaminating previously unoiled areas. The observation is significant as this indicates that within one week much of the oil had been stabilized.

Systematic visual observations of the distribution of surface oil along staked profile lines on the Bay 11 beach were made over the three-year period (1981-83) to provide: (1) detailed information on the spatial variability of oil cover and (2) input to the development of oil budget estimates. The first mapping survey was conducted on 26 August 1981, seven days after the release of oil (Fig. 2a). Heavy surface oil coverings are apparent in two sections of the intertidal zone. The first section is the upper one-third of the intertidal zone, near the high-water line, and the second is a gravel ridge on the low-tide terrace in the lower one-third of the intertidal zone. These two sections are separated by a comparatively oil-free area (Fig. 3a), which is composed of fine sediments (silt and sand) and is affected by surface run-off from the adjacent tundra backshore. Some oil was visible on the sediments below the mean low-water level, having been deposited there during lower low tides that had occurred after the oil release.

Comparison of the 1981 and 1982 maps (Figs. 2a and 2c) indicates that significant reductions in the surface oil distribution had occurred, although the total area of oil cover increased (Table 2) due to redistribution above the line previously reached by oil. The areas of fine sediment and those affected by surface run-off showed the greatest reduction in oil cover, whereas areas of coarse sediment, particularly in the upper half of the intertidal zone, showed the least change.

Although the areas of oil concentration were reduced significantly between 1982 and 1983 (Figs. 2c and 3c), the gross changes were similar to previous years in that a broad area of comparatively clean sediments was present in the mid-intertidal zone and areas of heavy oil cover were located in association with coarse sediments in the upper and lower sections of the intertidal zone. A major element of the 1983 oil distribution was an asphalt pavement that had formed on the beach face of the upper intertidal zone (Fig. 4) subsequent to the 1982 survey and observations. The pavement accounted for half (325 m^2) of the total area with a heavy oil cover (75-100%) in 1983 (615 m^2).

The total area of oiled shoreline and the mapped areas associated with each of the four oil-cover classes for each of the three surveys are listed in Table 2. The most significant features of this data set are: (1) the noticeable decrease in the total area of surface oil between 1981 and 1983 (only 45% of the originally oiled area retained an oil cover), and (2) the large decrease in the moderate-to-heavy and the heavy oil cover categories.

The oil distribution data can also be used to provide estimates of changes in the oil budget of the beach after three years. The 100%EA values (Table 3) indicate that approximately 70% of the 1981 oil remained in 1982 and approximately 30% remained in 1983. Although the estimates are simplified, they provide an index of the oil reductions that occurred by natural processes at this site.

Changes in Oil-in-Sediment Concentrations

Repetitive surface and subsurface samples were collected in 1981, 1982 and 1983 (Tables 4a and 4b), and a set of additional surface samples was collected in 1983 (Table 4c). A significant feature of the data is the sample variability, which masks general trends and emphasizes the need for large numbers of samples to adequately represent true oil-in-sediment content (Humphrey, 1984; Owens and Robson, 1987). Nevertheless some notable trends are evident:

- initial oiling levels were approximately one to two orders of magnitude higher in surface sediments than in subsurface sediments;
- oil concentrations ten days and one month after the initial oiling, on 28 August and 15 September respectively, were comparatively uniform in the across-shore direction;
- surface oil concentrations increased in the upper part of the

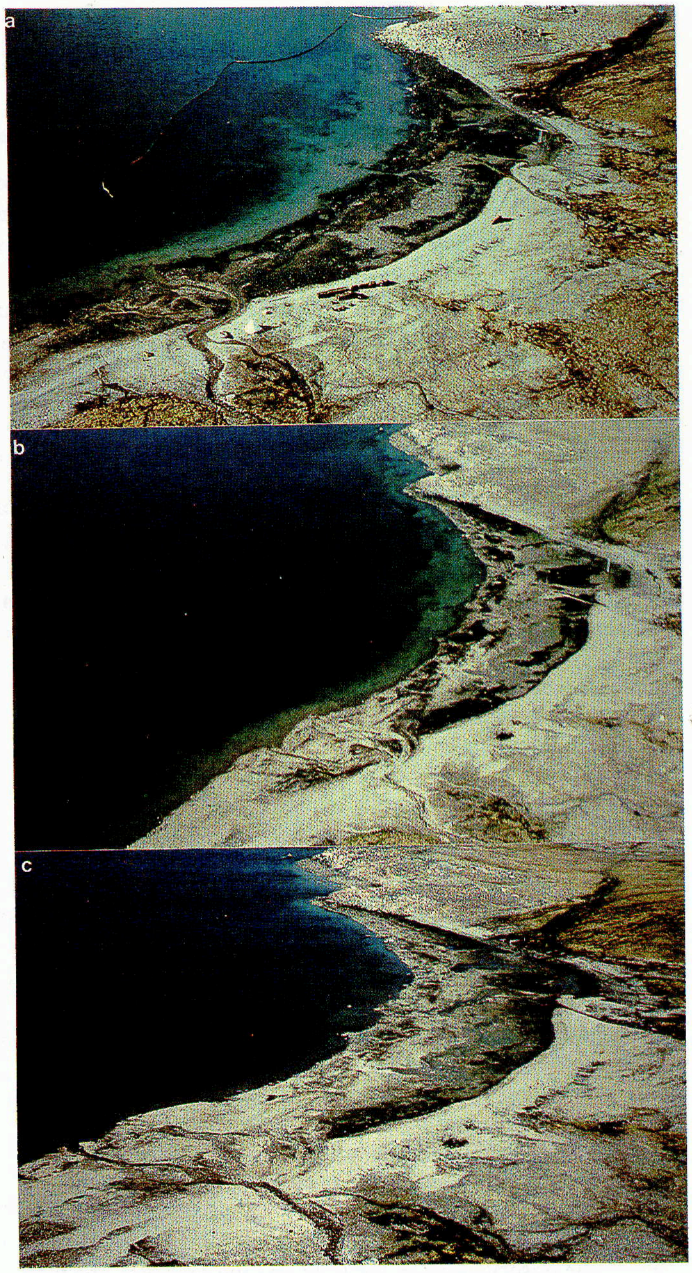

FIG. 3. Oblique aerial photographs of Bay 11: (a) 27 August 1981, 8 days after the spill; (b) 14 August 1982; (c) 14 August 1983. All photographs were taken at approximately 100 m altitude. The meteorological tower on the beach in (a) and (b) is approximately 4 m in height and is located in Figures 2a and 2b.

TABLE 2. Surface oil cover changes: 1981-83

Year	Total oiled area (m^2)	Oil distribution by class (m^2)			
		0.1-24%	25-49%	50-74%	75-100%
1981	8570	2015	1700	1145	3710
1982	9600	5200	1775	1320	1305
1983	3925	2120	840	350	615

TABLE 3. Changes in equivalent oil cover (100%EA) on beach: 1981-83

Year	Equivalent area of 100% oil cover (m^2)	Percent of initial oil
1981	4850	100
1982	3282	67
1983	1337	28

intertidal zone (the asphalt pavement area) prior to the 1983 samples, whereas in the lower intertidal zone surface oil concentrations decreased progressively after August 1981; and

- some increases in subsurface oil concentrations occurred during the sampling period in the middle and upper sections of the intertidal zone.

The long-term trends can be seen more clearly if the results are interpreted in the context of the beach morphology that characterizes this section of shoreline. In 1983 samples were collected for total hydrocarbon analyses in the three intertidal sections (ridge — trough — beach face) identified in Figure 4. The results of these analyses are combined in Table 4c with samples collected as part of the regular sampling program. The high oil-in-sediment concentrations on the beach face and on the low-tide beach ridge accurately reflect the mapped surface oil distribution pattern. The mid-tide trough is characterized by both low surface and subsurface oil concentrations and by a light oil or no oil cover. This stratified sample pattern (Table 4c) reflects the actual conditions more accurately than the set of repetitive samples, which were collected at fixed intervals along staked profiles. The value of the repetitive samples is primarily in the provision of a time-series of mean oil-in-sediment concentrations (Tables 5 and 6).

From the observations in the field and the results of the total hydrocarbon analyses it is evident that there was a remobilization

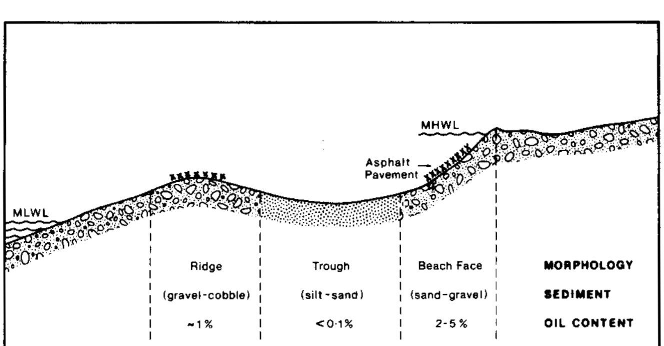

FIG. 4. Schematic of relationship between beach morphology, sediment type and surface oil concentrations (% oil in sediment by weight) in August 1983 along Profile 5 (Fig. 2c).

TABLE 4. Intertidal total extractable hydrocarbons (oil in sediment by weight: $mg \cdot kg^{-1}$)

Date	Upper intertidal zone	Middle intertidal zone	Lower intertidal zone
(a) Mean of repetitive surface sediment samples (based on 3 samples collected in each zone from the upper 2 cm; sample locations shown on Fig. 2)			
19 Aug 1981*	28000	19300	4850
20 Aug 1981	8830	3790	8600
28 Aug 1981	7010	7980	4950
15 Sept 1981	7060	6810	3770
10 Aug 1982	8370	2970	1860
16 Aug 1983	28600	5980	990
(b) Mean of repetitive subsurface sediment samples (based on 3 samples collected in each zone from the 5-10 cm depth interval)			
20 Aug 1981	263	93	146
28 Aug 1981	2050	293	356
15 Sept 1981	96	310	271
10 Aug 1982	2670	310	126
16 Aug 1983	710	1270	424
(c) Mean values of surface samples collected in 1983 in different morphological segments of the intertidal zone (see Fig. 4)			
	No. of samples	Surface	Subsurface
Beach face	6	19800	1240
Mid-beach trough	3	480	10
Lower beach ridge	4	7900	2600

*Mean of 2 samples from each zone.

TABLE 5. Time series of mean total extractable hydrocarbon concentrations and computed oil volumes: 1981-83

Date	No. of Samples	Mean surface total hydrocarbon concentration ($mg \cdot kg^{-1}$)	Surface oil volume	
			100%EA method	Volume method
19 Aug 1981	6	17400	$<5.3\,m^3>$	5.3 m^3
20 Aug 1981	9	7070	—	2.2
28 Aug 1981	9	6650	—	2.0
15 Sept 1981	9	5880	—	1.8
10 Aug 1982	9	4400	3.6	1.5
16 Aug 1983[a]	9	11900	—	1.6
16 Aug 1983[b]	10	4800	—	0.6
16 Aug 1983[c]	19	8150	1.5	1.1

[a]Samples collected at the same 9 locations as the previous sample sets.
[b]Samples at 10 additional selected locations.
[c](a) + (b)

and redistribution of the oil in the intertidal zone after the second year's observations, in 1982, and prior to the 1983 survey. The maximum single concentration measured on the asphalt pavement in 1983 was 58 000 $mg \cdot kg^{-1}$ (approximately 6% oil in sediment by weight). This remobilization occurred even though the stranded oil was apparently quite stable within a short period following the oiling of the beach.

TABLE 6. Time series of mean subsurface total extractable hydrocarbon concentrations: 1981-83

Date	No. of samples	Mean subsurface total hydrocarbon concentrations ($mg \cdot kg^{-1}$)
20 Aug 1981	9	186
28 Aug 1981	9	900
15 Sept 1981	9	226
10 Aug 1982	9	1030
16 Aug 1983[a]	9	803
16 Aug 1983[b]	10	1920
16 Aug 1983[c]	19	1390

Note: (c) = (a) + (b).

Budget of Oil on the Shore

The development of an oil spill budget for the initial few days is difficult, due to the rapidly changing behaviour and characteristics of the oil. It also is of lesser importance when considering oil fate in terms of years, as was the case in this study. Nevertheless, this information is discussed to demonstrate the derivation of the budget numbers used for yearly comparisons and to illustrate the variability encountered.

Deductive Accounting: Seventy-four drums, or approximately 15 m^3 of oil, were discharged on the water surface on 19 August 1981. Fifty-eight drums of oil-in-water emulsion were recovered from the water surface by the evening of 21 August. This equates to 27.2 drums of crude oil, or approximately 5.5 m^3. The estimate of oil losses due to dissolution during the discharge is 0.26 m^3; loss due to evaporation on the water surface during the 6 h discharge is estimated at 1.95 m^3 and during the next 18 h at 0.45 m^3 (Dickins *et al.*, 1987). Not including other losses that may have occurred on the shoreline, this calculation fails to account for 6.84 m^3 of oil, and this residual volume is taken as a deductive approximation of the amount of oil that remained on the beach by the low tide on the evening of 21 August.

Calculation of Initial Surface Oil Budget Using Total-Hydrocarbon Analysis Results: The mean total extractable hydrocarbon values derived from the analysis of six samples taken on 19 August and of nine samples collected on 20 August are contained in Table 5. Surface oil budget calculations using the volume method, based on these data and on the distribution of oil on 26 August, produce oil volumes of 5.3 m^3 and 2.2 m^3 for 19 and 20 August respectively. The dramatic reductions in the t-h concentrations and in the computed surface oil budgets indicate that the beach rapidly reached its maximum loading level. Some portion of the stranded oil was refloated and would have been collected and some of the oil would have penetrated into the subsurface sediments.

Budget of Subsurface Oil: No subsurface samples were collected on 19 August, but some were obtained from the same location as the surface samples on subsequent collection dates (Table 6). Mean subsurface oil values increased from 170 $mg \cdot kg^{-1}$ on 20 August to 900 $mg \cdot kg^{-1}$ on 28 August but dropped to 215 $mg \cdot kg^{-1}$ by 15 September 1981.

The subsurface oil content of the beach cannot be calculated accurately due to variability in the oil penetration depth. However, it is possible that the major portion of the oil unaccounted for could have migrated into the subsurface sediments of the Bay 11 beach. The surface samples were collected in the upper 2 cm; the subsurface samples were collected between 5 and 10 cm. Thus, 3 cm is unaccounted for in the sample design. The subsurface samples cover a larger depth range than the surface samples (5 cm vs. 2 cm). Using the volume method to calculate a subsurface sediment volume based on an 8 cm depth (2-10 cm) provides a value of 685.6 m^3. The assumed sediment density of 1.6 produces a total sediment weight of 1097 metric tonnes, or 1097 × 10(6) kg. The subsurface samples from 28 August 1981 have a mean of 900 $mg \cdot kg^{-1}$, so that the weight times the concentration gives a value of 987 × 10(6) kg. Converting to m^3 by multiplying by the density of 0.89 indicates an oil volume of 1.1 m^3. This assumes that the entire depth range from which the sample was collected has a total hydrocarbon concentration of 900 $mg \cdot kg^{-1}$. A similar calculation for 20 August, when the mean t-h concentration was 170 $mg \cdot kg^{-1}$, produces an oil volume of 0.2 m^3.

Initial Oil Budget: On the basis of this analysis we have developed a budget that reflects both our data and the field observations. The budget given in Table 7 reflects the period of initial oiling on 19-20 August 1981 and the situation on 28 August, when relatively stable conditions were reached in terms of oil retention in the intertidal zone. These estimates of 10.56 m^3 for an initial budget on 20 August and of 11.26 m^3 on 28 August, after the stranded oil became stabilized, are an approximation but are considered to be accurate within the context of the study. Given the difficulties of sampling variability on gravel beaches (Owens and Robson, 1987) and estimating the surface oil cover (Owens, 1984b), the initial surface budget for the stranded oil of 5.3 m^3 on 19 August and the subsequent surface plus subsurface value of 3.1 m^3 for 28 August are considered acceptable.

TABLE 7. Initial budget estimates of the fate of the spilled oil (m^3)

	19 August	20 August	28 August
Spilled	15.0		
Evaporated/dissolved		2.66	2.66
Recovered		5.5	5.5
Oil on the surface	5.3	2.2	2.0
Oil in the subsurface		0.2	1.1

Oil Budget 1981-83: On the basis of the initial oil budget and of the changes in the 100%EA values and the mean t-h concentrations of the beach sediments, it is possible to estimate the volume of surface oil that remained on the beach two years after the spill (Tables 5 and 8). It must be remembered that the two-year calendar period over which these changes have taken place in fact represents a total of only approximately 28 weeks, or 6 months, of open-water conditions at this site. These estimates relate to the volume of surface oil only, as no data are available on the areal distribution of subsurface oil.

TABLE 8. Estimated volume of stranded oil: 1981-83 (based on changes in the 100%EA value: Table 3)

Date	Change from initial oil volume (%)	Estimated oil volume (m^3)
19 Aug 1981	100	5.3
11 Aug 1982	67	3.6
15 Aug 1983	28	1.5

A budget based on the 100%EA computed oil volumes assumes that if the oil volume of 5.3 m^3 on 19 August 1981 is equivalent to 100%, then the progressive reduction of that initial value, as derived from Table 3, represents a volumetric change in the amount of stranded oil remaining on the beach. This approach produces a value of 1.5 m^3, or 28%, of oil remaining on the beach in mid-August 1983. This figure is equivalent to approximately 10% of the initial volume of oil released on the water surface in August 1981 and approximately 30% of the initial volume of stranded oil.

The volume method indicates a sharp decrease in the oil volume from 19 to 20 August 1981, followed by a small but progressive reduction to the last value for 16 August 1983 (Table 5). The combined mean t-h value (c) is considered more representative of the oil-in-sediment concentrations, as this incorporates the results of 19 analyses, and this provides a surface oil volume of 1.1 m^3, approximately 7% of the volume of oil released and 20% of the initial volume of stranded oil.

A characteristic feature of the intertidal zone during 1983 was the presence of an asphalt pavement that extended 150 m alongshore in the upper intertidal zone (Fig. 5). The area of the pavement was 325 m^2 and the thickness varied between 3 and 10 cm. An estimate of the volume of oil contained in the asphalt pavement was made using the volume method with an assumed pavement thickness of 5 cm. This approach produces an oil volume of 0.58 m^3 (Table 9). Applying the same method but using a sample depth of 2 cm for the remaining area of the oiled beach produces an oil volume of 0.45 m^3. The combined total of 1.03 m^3 closely approximates the computed overall oil volume of 1.1 m^3 in August 1983 (Table 5). The asphalt pavement is the most obvious visual feature of the intertidal zone in 1983 and contains approximately half of the total volume of oil that remained on the beach within 8% of the total oiled area. This volume of oil in the pavement is on the order of 20% of the oil originally stranded in 1981.

FIG. 5. Asphalt pavement in the vicinity of Profile 5 (Fig. 2c) on 14 August 1983.

Changes in the Oil Chemistry

Detailed chemical analyses were performed on a suite of 6 repetitive samples of the Bay 11 beach surface sediments collected one day, one month and one year after the stranding of oil. A more extensive set of 25 surface and subsurface sediment samples was collected in 1983, two years after the stranding. This data set is listed in Table 10.

TABLE 9. Estimated oil budget for Bay 11 intertidal zone, August 1983

	Area (m^2)	Mean total hydrocarbon concentration (mg·kg^{-1})	Computed oil volume (m^3)
Asphalt pavement	325	20000	0.58
Remaining area	3600	3500	0.45
Total	3925	—	1.03

TABLE 10. Summary of chemical analyses and weathering ratios of Bay 11 beach sediment samples.

Sampling period (time after oil release)	Total oil concentration (ppm)	ALK/ISO*	SHWR*	AWR*
Original oil	—	2.5-2.8	2.5-2.9	2.5-3.0
One day	180000	2.6	2.5	—
	80000	2.7	2.8	—
	30000	2.8	2.9	—
	14000	2.7	2.5	—
	8000	2.7	2.5	—
	2000	2.8	2.4	—
One month (Sep 1981)	33000	2.8	1.9	—
	25000	2.9	1.5	—
	21000	2.7	1.8	—
	13000	2.7	1.6	—
	10000	2.8	1.5	—
	500	1.8	1.2	—
One year (Aug 1982)	7200	1.8	1.2	—
	4400	1.3	1.2	—
	3700	1.1	1.2	—
	2100	1.0	1.0	—
	1600	0.9	1.1	—
	700	0.6	1.1	—
Two years (Aug 1983)	19400	2.5	1.6	—
	17200	2.2	2.0	2.5
	13900	1.9	1.6	2.2
	13500	2.1	1.7	—
	12800	1.0	1.4	—
	7000	2.0	1.6	2.3
	6100	0.7	1.0	—
	5600	1.8	1.8	—
	3900	0.3	1.0	—
	3480	1.4	1.1	—
	1900	0.7	1.0	—
	1500	1.4	1.0	—
	1500	1.2	1.0	—
	1300	0.3	1.1	—
	900	0.4	1.1	1.1
	520	2.1	1.8	—
	400	1.0	1.0	1.0
	320	1.2	1.3	—
	270	2.1	1.7	—
	190	1.8	1.6	2.1
	80	0.7	1.2	—
	70	0.2	1.1	—
	40	0.4	1.2	—
	5.0	1.4	1.3	—
	4.0	1.4	1.3	3.5

*Defined in Table 1.

Analytical results confirmed that physio-chemical weathering (i.e., evaporation and dissolution) had begun immediately after the Bay 11 oil release and subsequent stranding, largely due to evaporation of lower molecular weight saturated and aromatic hydrocarbons (Figs. 6 and 7). The stranded oil sam-

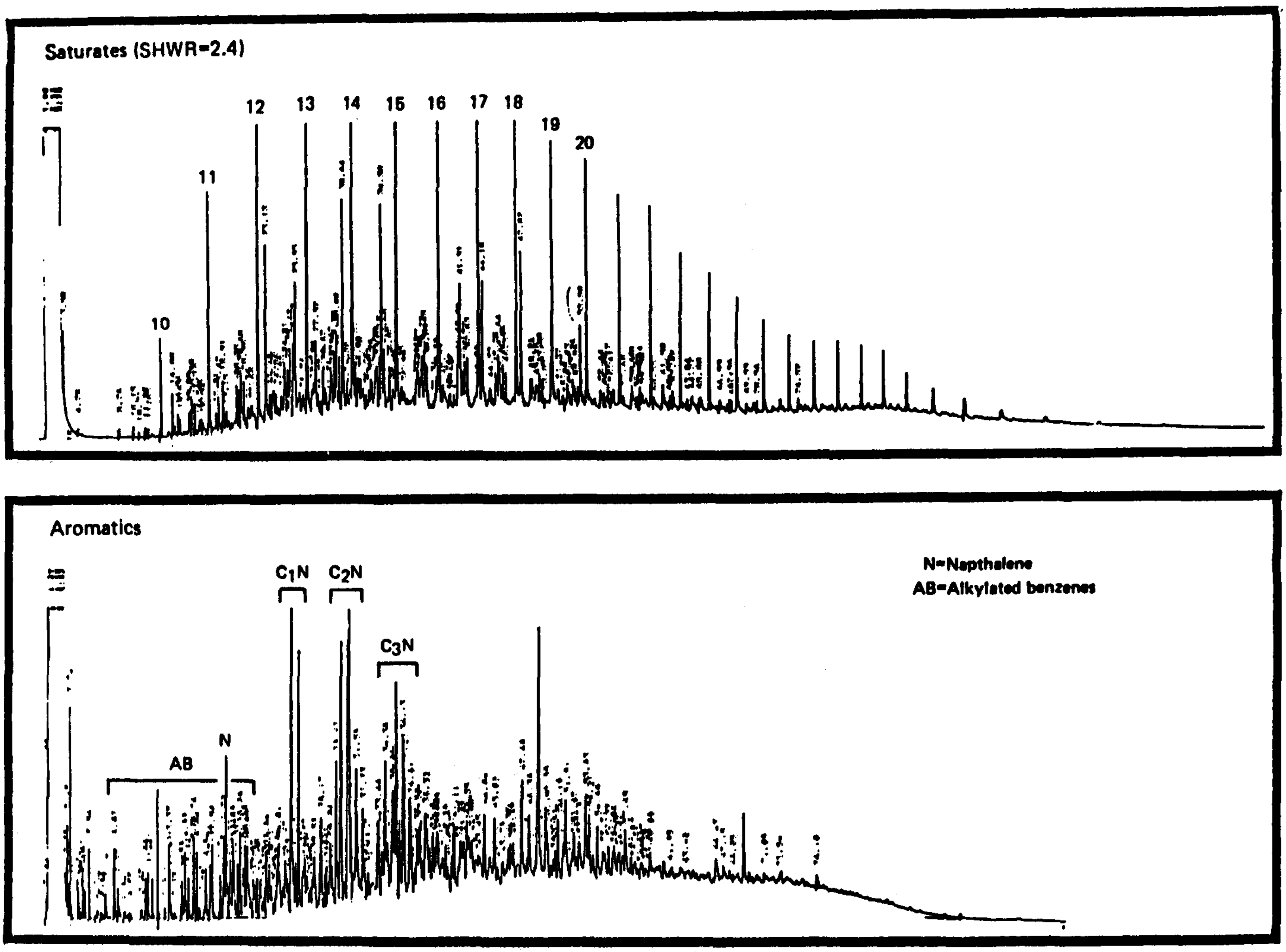

FIG. 6. GC^2 profiles of beached oil from Bay 11 one day after stranding.

pled one year after the spill had weathered significantly due to physio-chemical and biodegradative processes. Samples taken one day after the oil release exhibit SHWR values of 2.4-2.9, similar in range to the original value of 2.5-2.9 in the spilled oil (Table 10). Samples taken one month later exhibited SHWR values of 1.2-1.9, illustrating a substantial loss, due to evaporation, of the C_{10} through C_{17} normal alkanes. More substantial weathering was observed in samples of lower oil concentration, presumably due to the larger surface area available for evaporative loss. One year after the release the remaining oil had been nearly uniformly weathered to the point that the SHWR values are 1.0-1.2, indicating a near total loss of the C_{10} to C_{17} normal alkanes at all oil concentration levels.

The preferential loss of normal alkanes relative to the branched isoprenoid alkanes, due to biodegradation and resulting in lower ALK/ISO ratios, began one month after the oil release. Biodegradation of stranded oil residues one month after the spill was observed to occur only in the sample of lowest oil concentration (Table 10) which has an ALK/ISO ratio of 1.8. One year later, a dramatic decrease in the ALK/ISO ratio, with values of 0.6-1.8, compared with an original value of 2.5, attests to the important role of biodegradation in reducing the *n*-alkane content of the oil residues. The degree of biodegradation was inversely proportional to the oil concentration. Thus, one year after the spill the existence of a heterogeneous weathering regime was indicated by a significant degree of biodegradation on the beach in most of the samples with, at the same time, several illustrations of relatively undegraded oil still present.

With an increased intensity of sampling two years after the spill, in 1983, the heterogeneous chemical nature of the stranded oil became quite apparent. This patchiness evidently corresponds with the absolute oil concentration (Table 10). Areas of high concentrations of oil are, for the most part, characterized by a less weathered oil. Examples can be seen in samples with an oil content ranging from 13 500 to 19 400 ppm. Both the high SHWR (1.6-2.0) and high ALK/ISO ratios (1.9-2.5) indicate that weathering was less extensive where large oil concentrations persisted. These 1983 values represent oil nearly as "fresh" as that sampled in September 1981, one month after the stranding. However, areas of low concentration sampled on the lower beach face were highly weathered from both physio-chemical (SHWR) and biodegradative (ALK/ISO) aspects. An illustration of the range of chemical composition encountered two years after the stranding of the oil is shown in Figure 8.

The observation of extensive, albeit patchy, biodegradation on the beach itself is important, as subtidal biodegradation was seen to be an insignificant weathering process over the two-year post-spill period (Boehm *et al.*, 1985). The existence of

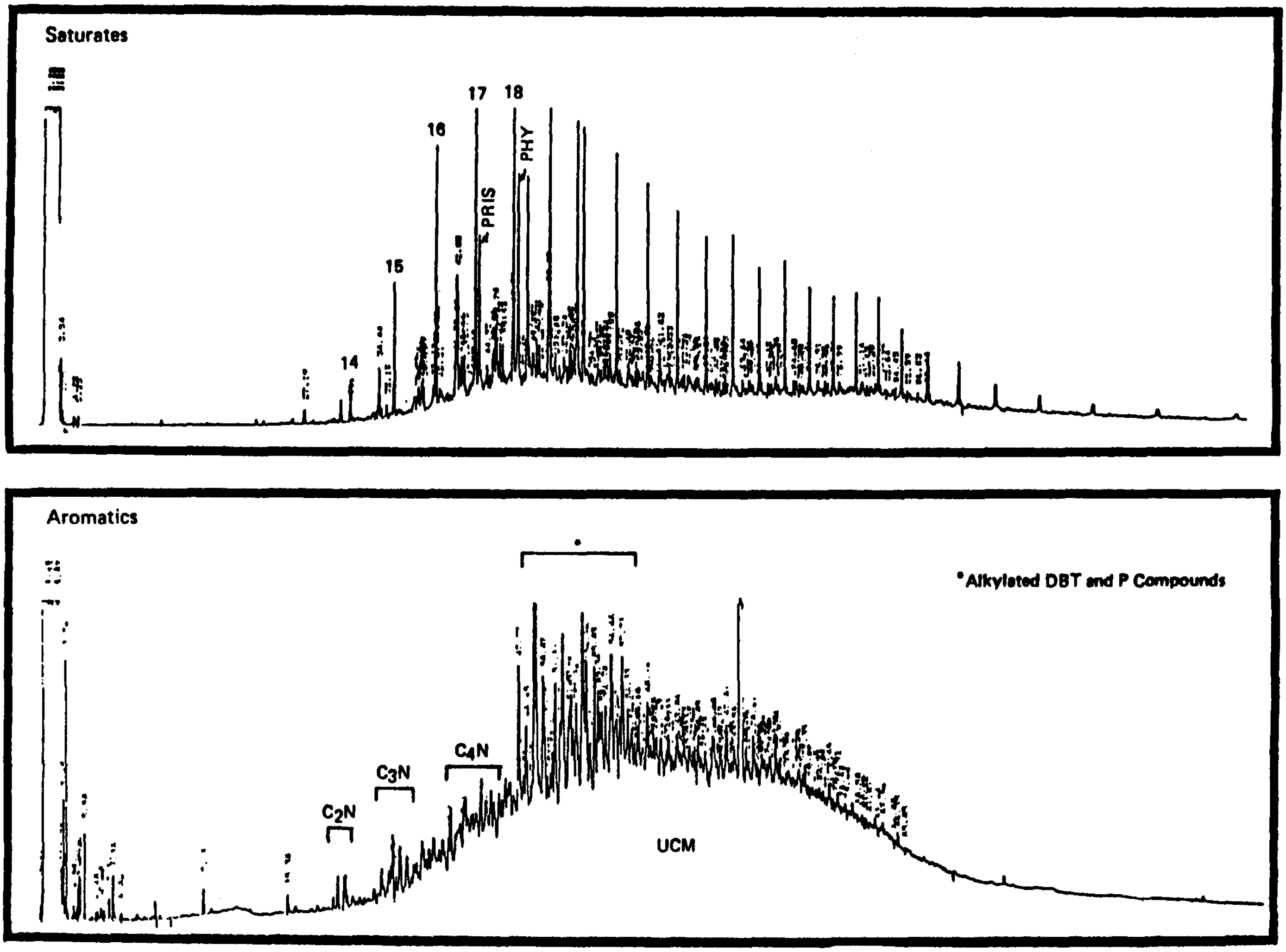

FIG. 7. GC^2 profiles of beached oil from Bay 11 one month after stranding.

biodegraded oil in the subtidal environment was apparently almost solely due to erosion of weathered oil from the intertidal zone and deposition in the adjacent subtidal zone over time.

DISCUSSION

Previous Studies

The principles of natural self-cleaning as a function of wave energy levels at the shoreline have been recognized for many years. Despite the large number of spills documented and investigated, few time-series data sets have been developed on the fate and persistence of stranded oil. In the case of the *Arrow* and the *Amoco Cadiz* incidents, ongoing studies were curtailed by the effects of second spills on the same coasts (the *Kurdistan* and *Tanio* respectively). The fate of stranded oil is considered by Vandermeulen and Gordon (1976) to be related to tidal flushing and interstitial water movement that transport oil into the water column. The rates at which this transport takes place are a function primarily of wave energy levels at the shoreline (Owens, 1978, 1985; Thomas, 1977; Tsouk *et al.*, 1985). However, little data exist on changes in the oil-in-sediment concentrations of beach sediments or on changes in the distribution of oil on the shoreline, other than lengths of oiled coast. Similarly, there have been few attempts to budget the fate of spilled oil, other than at a very general scale, or to produce data sets that permit estimation of the changes in the volume of stranded oil through time.

Following the *Arrow* oil spill in Chedabucto Bay in 1970, two samples were collected from an asphalt pavement at Arichat, Nova Scotia, three months after the oil was stranded. Analysis of these samples produced values of 40 000 and 50 000 $mg{\cdot}kg^{-1}$ (Owens, 1971). That asphalt pavement was subsequently removed by heavy equipment so that no further data were available from this site. Visual observations three years after the same spill, at Black Duck Cove and at Crichton Island, Nova Scotia, indicated the presence of asphalt pavements (Owens, 1978). Sediment samples were collected at that time from different intertidal locations, and Rashid (1974) noted that the samples from the low-energy environment were relatively unweathered in comparison with the original oil. Vandermeulen and Gordon (1976) show that after five years the amounts of oil in pavement samples in this area were $11.6 \pm 8\%$ ($wt{\cdot}wt^{-1}$) and that oil-in-sediment concentrations ranged from 6700 to 15 800 $mg{\cdot}kg^{-1}$. Samples collected in the following year in the same area produced oil-in-sediment concentrations up to 25 000 $mg{\cdot}kg^{-1}$ (Thomas, 1977).

Large asphalt pavements were formed following the *Metula*

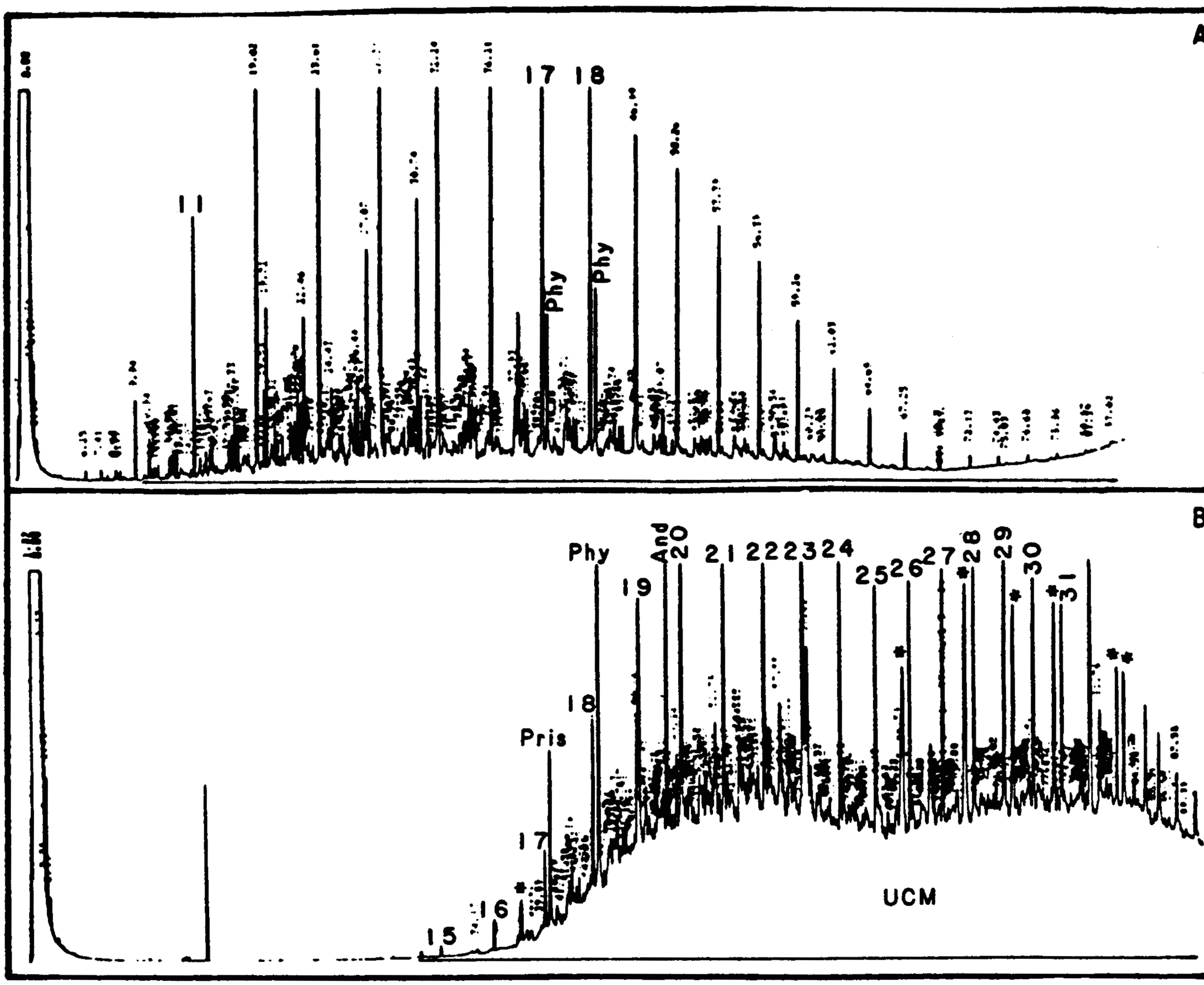

FIG. 8. GC[2] trace of Bay 11 beach sediments; showing undegraded, unweathered oil (A) and weathered and degraded oil (B) two years after stranding.

spill in the Strait of Magellan, Chile. Data from asphalt pavement sediment samples collected 1½ years after the spill provide values in the range of 10 000-80 000 $mg \cdot kg^{-1}$ oil in sediment concentrations, with half of the values between 20 000 and 50 000 $mg \cdot kg^{-1}$ (Blount, 1978; Owens *et al.*, 1986b). Visual observations 6½ years after the event (Gundlach *et al.*, 1982) indicate that an asphalt pavement up to 15 cm thick and 20-40 m wide was still present at one site in the upper intertidal zone.

A small spill of 130 m^3 of diesel fuel on a sheltered low-energy beach in Van Mijenfjord, Spitzbergen, in 1978 was sampled two years later (Gulliksen and Taasen, 1982). Sediment samples from the top 10 cm of the beach surface adjacent to the source produced values of 826 and 5892 $mg \cdot kg^{-1}$ in the upper intertidal zone and 147 $mg \cdot kg^{-1}$ in the middle zone. These data are directly comparable to the experimental results discussed in this paper, as the area has a similar ice-dominated environment, fetch areas are in the same order of magnitude and the beach sediments are sandy gravels.

Data on the weathering of stranded oil have been presented by a number of authors to illustrate the changing composition of oil with time. Field and laboratory studies have shown that saturates are weathered more rapidly than aromatics and that the asphaltenes are more persistent and decrease more slowly than the resin or hydrocarbon fractions (Boehm *et al.*, 1981; Calder and Boehm, 1981; Fusey and Oudot, 1984).

Budgets of Stranded Oil

Either measurements of the total hydrocarbon concentrations of oil in sediments or maps of the surface oil cover are essential elements of a data base for the investigation of the fate and persistence of stranded oil. A major difficulty with large oil spills is that accurate data sets are difficult to develop due to the variety of shoreline types that may exist in an area, the continuously changing distribution of the oil in the initial post-spill period and the difficulties of obtaining repeatable results from shorelines. For an initial budget of the oil that remains at the shoreline, it is necessary to account for the volumes of oil that evaporate and are lost by dissolution, suspension and dispersion into the water column before the oil reaches the shoreline. Budget estimates must relate to the volumes of oil (1) that are initially stranded and retained on the shoreline within the first 48 h and (2) that stay after a period in the order of seven days. This is necessary because major changes in the volume of oil that remains on the shoreline occur during this initial period. If cleanup operations are undertaken, then it is necessary to estimate the total volume of sediment that must be removed or the volume of oil that has to be dispersed.

Time-series data are required to determine changes in the surface area contaminated by the stranded oil and in the concentrations of that oil. Surface and subsurface samples should be collected for total hydrocarbon analysis from both the intertidal and subtidal environments. The subsurface and surface distribution of stranded oil is usually extremely variable, so the program of data collection should take into account the level of accuracy required for use of the information. The integration of one data set in which analyses are conducted to accuracies of parts per million for oil concentrations with another that has accuracies in the order of 5 or even 10% to estimate the surface oil cover would appear initially to be inappropriate. In reality these two data sets are complementary and provide the basis from which estimates can be made of the volume of oil remaining on the shoreline through time.

The field activities and observations on this relatively small section of coast show that a simple estimate of the length of shoreline that is oiled is of little value other than to provide a measure of the total contamination in aesthetic terms. In order to provide information that can be of value for the development of cleanup decisions or for an assessment of the potential impact or long-term fate of stranded oil, it is necessary to estimate (1) the length of shoreline that contains oil, (2) the surface area per unit length of oil contamination and (3) the volume of oil based on the areal coverage, the surface and subsurface amounts of oil and total hydrocarbon concentrations. At this site the actual length of visually contaminated shoreline, based on ground observations with greater than 25% oil cover, was reduced from 275 to 190 m (i.e., by 30%) between 1981 and 1983. If an areal survey of an extensive length of coast were conducted with similar results, the interpretation would suggest a reduction in the contamination probably in the order of 30%, expressed as a length. By contrast, the field data show that: (1) the reduction of the contaminated surface area at this site was in the order of 55% and (2) the reduction of the estimated volume of stranded oil was in the order of 80%.

The Fate of Stranded Oil

Many commentators (for example, Seip, 1984) have observed that once the most obvious effects of stranded oil have disappeared the recovery rate is apparently very slow. This observation applies to many of the large spills observed and documented. Few detailed explanations of the processes that effect the changes in the character and the volume of oil at the shoreline have been presented. Vandermeulen (1977) notes that the general pattern following the *Arrow* spill (a weathered bunker fuel) was a short-term removal by wave action, which resulted in the removal of 50% of the stranded oil in one year, 75% within three years and 95% within seven years.

The leaching of oil from the intertidal zone of the Bay 11 beach had taken place as a result of wave-induced processes and by surface run-off from the backshore across the beach. The reduction in the volume of oil in the beach was accompanied by an increase in the total hydrocarbon concentrations found in the adjacent subtidal sediments (Boehm *et al.*, 1984). Samples analyzed in 1982 yielded values in the range of 2-10 ppm, with the highest values (up to 70 ppm) located adjacent to Profile 6 in water depths of 3 and 7 m. The analytical results from 1983 (Table 11) show a sixfold increase in the total hydrocarbon concentrations in the subtidal sediments of this area, as compared to the results of analyses conducted on samples collected in 1981 (Boehm *et al.*, 1982). The highest concentrations were again in the vicinity of Profile 6 in the area between the 3 and 7 m depth contours. As previously noted, geochemical analysis of the subtidal samples indicates that the oils sampled in the subtidal sediments were biodegraded as a result of processes that occurred when the oils were resident in the intertidal zone (Boehm *et al.*, 1985).

By mid-August 1983, less than 10% of the original volume of spilled oil remained on the shoreline, so that by this time more than 60% of the spilled oil had been lost to the atmospheric and oceanic environments. This change in the distribution of the spilled oil is significant because only 20% of the oil stranded on the shore zone remained after a period of approximately 28 weeks, even though this environment is regarded as having a very sheltered wave climate.

The generally accepted pattern for medium or heavy oils is one of the rapid removal of the stranded oil from the intertidal zone, where wave energy levels provide sufficient mechanical energy, and of very slow rates of degradation, by biological or biochemical processes, of oil stranded above the limits of normal wave action or in low-energy environments (Owens, 1978). This concept is elaborated by Owens (1985) to take into account rates of shoreline change and is pursued further by Fusey and Oudot (1984), who developed a semi-quantitative graphic model to evaluate the relative roles of mechanical removal and of biodegradation of stranded oil on the basis of field experiments on a sheltered coast in northwest France.

Primary problems that limit the comparison of different data sets from experiments or from spills include the effects of cleanup operations, contamination from other sources, differences in oil types, environmental conditions and differences in measurement or analytical procedures. Despite these potential

TABLE 11. Analytical results from subtidal sediment samples collected on a microbiology transect from the centre of Bay 11, 13 August 1983

Station	Depth below LWL* (m)	Distance from LWL* (m)	Estimated petroleum concentration ($mg \cdot kg^{-1}$)
16	1.3	2	87
15	1.5	4	44
14	2.4	8	410
13	4.0	23	120
12	4.5	37	36
11	4.6	40	42
10	4.6	44	40
9	5.5	63	29
8	6.1	76	4.5
7	6.4	84	4.4
6	6.9	92	0.9
5	7.6	104	1.7
4	9.1	123	1.2
3	9.1	125	0.8
2	10.6	136	0.8
1	11.3	143	1.7

*LWL = low water line.

problems, there does appear to be some consistency between data sets from different studies — for example, (1) the analysis of sediment samples from asphalt pavements from four different environments produces total hydrocarbon contents generally in the range of 1-5% (Owens *et al.*, 1986b), and (2) rates of weathering of intertidal oil appear to be a function of oil concentrations, low rates being associated with high concentrations (Boehm *et al.*, 1981, 1985).

The processes that control the fate and persistence of the stranded oil are still poorly understood. Leaching by ground water that flows from the tundra backshore through the intertidal zone is a significant oil removal process. Large areas of sheen have been observed on the water surface adjacent to Bay 11 following periods of rain with offshore wind conditions (B. Humphrey, pers. comm. 1984). Degradation of the oil by biological or biochemical processes at this location at the end of the observation period was active but was an important weathering process only for sediments with relatively low oil concentrations. Oil in the asphalt pavements had weathered little following the initial loss of the low molecular weight hydrocarbons, and this "pavement oil" was relatively "fresh" in character. The physical processes of erosion and removal by wave action and by ground-water leaching are believed to be the primary agents that account for the reductions of oil concentrations and volumes in the intertidal zone.

CONCLUSIONS

This study leads to the following conclusions:

1. The fate of the 15 m^3 of crude oil released on the nearshore waters of Ragged Channel was initially (19-22 August 1981) in the order of: one-third (5.5 m^3) recovered by the cleanup activities on the water, an estimated one-third (5.3 m^3) stranded on the intertidal zone and one-third, not directly accounted for, lost to the ocean and the atmosphere by dissolution and evaporation. Within ten days of the release, the estimated volume of stranded oil on the beach surface had decreased to 3.1 m^3. By the end of the study period (August 1983), approximately six open-water months after the spill, less than 10% (1.1 m^3) of the volume of the oil released on the Bay 11 water surface remained on the beach surface.

2. An aerial reconnaissance survey over the study area, similar to that which would be undertaken following a real spill situation, indicated that at the end of the study period the intertidal zone was still heavily oiled. The detailed field observations, however, have shown that significant changes took place in both the area of surface oil cover and the volume of oil that remained on the shoreline.

3. The oil that reached the shoreline did not immediately adhere to the sediments but appeared to have stabilized within one week. The initial areas of heavy oil cover were on the beach face and on the low-tide terrace, associated with the distribution of coarse sediments. These sections of beach remained areas of heavy oil cover and of high oil-in-sediment concentrations throughout the study period.

4. In terms of the distribution of oil on the intertidal zone, over the six-month open-water period of observations the surface cover of oil was reduced by approximately half. The changes in the surface area of oil and in the volume of contamination are of great importance, as these occurred over a cumulative open-water period of only approximately six months in a very sheltered environment. The reduction of stranded oil resulted primarily from the physical processes associated with wave activity and ground-water leaching.

5. A major change in the physical character of the stranded oil took place with the development of an asphalt pavement in the upper intertidal zone on the beach-face slope. Total hydrocarbon concentrations on the beach face increased significantly by the third open-water observation period (1983), with values in the order of 2-5% oil in sediment by weight. At the time of the 1983 survey the volume of oil within the pavement (0.6 m^3) was approximately half of the total volume of stranded oil (1.1 m^3), although the pavement accounted for only 8% of the total oiled area at the time.

6. The results from associated studies in this series of BIOS experiments indicate that the oil was deposited in the adjacent nearshore bottom sediments and that oil concentrations in 1983, after the first two inshore sample periods (1981 and 1982), had increased sixfold.

7. The initial weathering in the days immediately following the spill was due largely to evaporation of lower molecular weight hydrocarbons (C_1 to C_{10}). Subsequent weathering over the next two years progressed more rapidly in areas with low oil concentrations (1%). Oil in areas with high oil concentrations had weathered little after two years, as was determined from a comparison of samples collected one month after the spill.

8. Biodegradation was observed to be an important factor in reducing the *n*-alkane content of oil in samples collected after one year. Over the study period the degree of biodegradation was inversely proportional to the oil concentration.

ACKNOWLEDGEMENTS

This study was undertaken as part of the BIOS (Baffin Island Oil Spill) Project, a part of the AMOP (Arctic Marine Oilspill Program) series of studies. The lead agency for this series of studies has been the Environmental Protection Service of Environment Canada. Substantial support and funding were made available from numerous industry and government agencies both within Canada and from other countries. Considerable assistance was provided throughout the field studies by a large number of individuals, but particular acknowledgement is made to the field and laboratory work conducted by Blair Humphrey and his associates of Seakem Oceanography.

REFERENCES

BLOUNT, A.E. 1978. Two years after the "Metula" oil spill, Strait of Magellan, Chile. Department of Geology, University of South Carolina, Columbia. Unpubl. Technical Report No. 16-CRD. 207 p.

BOEHM, P.D. 1983. Chemistry 2: Analytical biochemistry — 1982 study results. Baffin Island Oil Spill (BIOS) Project Working Report 82-2. Ottawa: Environmental Protection Service, Environment Canada. 210 p.

———, FIEST, D.L., and ELSKUS, A. 1981. 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. Brest (France): Centre Oceanologique de Bretagne. 159-173.

BOEHM, P.D., FIEST, D.L., and HIRTZER, P. 1982. Chemistry 2: Analytical biogeochemistry — 1981 study results. Baffin Island Oil Spill (BIOS) Project Working Report 81-2. Ottawa: Environmental Protection Service, Environment Canada. 354 p.

BOEHM, P.D., STEINHAUER, W., COBB, D., DUFFY, S., and BROWN, J. 1984. Chemistry 2: Analytical biogeochemistry — 1983 study results. Baffin Island Oil Spill (BIOS) Project Working Report 83-2. Ottawa: Environmental Protection Service, Environment Canada. 139 p.

BOEHM, P.D., STEINHAUER, W., REQUEJO, A., COBB, D., DUFFY, S., and BROWN, J. 1985. Comparative fate of chemically dispersed and untreated oil in the Arctic: Baffin Island oil spill studies 1980-1983. In: Proceedings 1985 Oil Spill Conference. Washington, D.C.: American Petroleum Institute Pub. No. 4385. 561-570.

BOEHM, P.D., STEINHAUER, M.S., GREEN, D.R., FOWLER, B., HUMPHREY, B., FIEST, D.L., and CRETNEY, W.J. 1987. Comparative fate of chemically dispersed and beached crude oil in subtidal sediments of the arctic nearshore. Arctic 40 (Supp. 1):133-148.
BROWN, D.W., RAMOS, L.S., FRIEDMAN, A.J., and MACLEOD, W.D. 1979. 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 No. 519. 161-167.
BUCKLEY, J.R., DE LANGE BOOM, B.R., and REIMER, E.M. 1987. The physical oceanography of the Cape Hatt region, Eclipse Sound, N.W.T. Arctic 40 (Supp. 1):20-33.
BUNCH, J.N., and CARTIER, T. 1984. 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. Ottawa: Environmental Protection Service, Environment Canada. 44 p.
CALDER, J.A., and BOEHM, P.D. 1981. The chemistry of "Amoco Cadiz" in Aber Wrac'h. In: Proceedings of the International Symposium, "Amoco Cadiz" Fates and Effects of the Oil Spill. Brest (France): Centre Oceanologique de Bretagne. 149-158.
CALDER, J.A., LAKE, J., and LASETER, J. 1978. Chemical composition of selected environmental and petroleum samples from the "Amoco Cadiz" oil spill. NOAA/EPA Special Report. Washington, D.C.: NOAA. 21-84.
CRETNEY, W.J., WONG, C.S., GREEN, D.R., and BAWDEN, C.A. 1978. Long-term fate of a heavy fuel oil in a spill-contaminated B.C. coastal bay. Journal Fisheries Research Board, Canada 35(5):521-527.
DICKINS, D.F. 1987. Ice conditions at Cape Hatt, Baffin Island. Arctic 40 (Supp. 1):34-41.
______, THORNTON, D.E., and CRETNEY, W.J. 1987. Design and operation of oil discharge systems and characteristics of oil used in the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):100-108.
EIMHJELLEN, K., and JOSEFSON, K. 1984. Microbiology 2: Biodegradation of stranded oil — 1983 study results. Baffin Island Oil Spill (BIOS) Project Working Report 83-6. Ottawa: Environmental Protection Service, Environment Canada. 58 p.
FUSEY, P., and OUDOT, J. 1984. Relative influence of physical removal and biodegradation in the depuration of petroleum-contaminated seashore sediments. Marine Pollution Bulletin 15(4):136-141.
GULLIKSEN, B., and TAASEN, J.P. 1982. Effect of an oil spill in Spitzbergen in 1978. Marine Pollution Bulletin 13(3):96-98.
GUNDLACH, E.R., and HAYES, M.O. 1978. Vulnerability of coastal environments to oil spill impacts. Marine Technology Society Journal 12(4):18-27.
GUNDLACH, E.R., and REED, M. 1986. Quantification of oil deposition and removal rates for a shoreline/oil spill interaction model. Proceedings of 9th Arctic Marine Oilspill Program (AMOP) Technical Seminar, June 10-12. Edmonton: Environment Canada. 65-76.
GUNDLACH, E.R., FINKELSTEIN, K.J., and SADD, J.L. 1981. Impact and persistence of IXTOC-I oil on the south Texas coast. In: Proceedings, 1981 Oil Spill Conference. Washington, D.C.: American Petroleum Institute Pub. No. 4334. 477-485.
GUNDLACH, E.R., DOMERACKI, D.D., and THEBEAU, L.C. 1982. Persistence of 'Metula' oil in the Strait of Magellan six and one-half years after the incident. Oil and Petrochemical Pollution 1(1):37-48.
GUNDLACH, E.R., KANA, T.W., and BOEHM, P.D. 1985. Modeling spilled oil partitioning in nearshore and surf zone area. In: Proceedings 1985 Oil Spill Conference. Washington, D.C.: American Petroleum Institute Pub. No. 4385. 379-384.
HAYES, M.O., GUNDLACH, E.R., and D'OZOUVILLE, L. 1979. Role of dynamic coastal processes in the impact and dispersal of the "Amoco Cadiz" oil spill (March, 1978) Brittany, France. In: Proceedings 1979 Oil Spill Conference. Washington, D.C.: American Petroleum Institute Pub. No. 4308. 193-198.
HUMPHREY, B. 1984. Chemistry 1: Field sampling and measurements — 1983 study results. Baffin Island Oil Spill (BIOS) Project Working Report 83-1. Ottawa: Environmental Protection Service, Environment Canada. 64 p.
______, BOEHM, P.D., HAMILTON, M.C., and NORSTROM, R.J. 1987a. The fate of chemically dispersed and untreated crude oil in arctic benthic biota. Arctic 40 (Supp. 1):149-161.
HUMPHREY, B., GREEN, D.R., FOWLER, B.R., HOPE, D., and BOEHM, P.D. 1987b. The fate of oil in the water column following experimental oil spills in the arctic marine nearshore. Arctic 40 (Supp. 1):124-132.
KEIZER, P.D., AHERN, T.P., DALE, J., and VANDERMEULEN, J.H. 1978. Residues of Bunker C oil in Chedabucto Bay, Nova Scotia, six years after the "Arrow" spill. Journal Fisheries Research Board, Canada 35(5):528-535.
MEERES, L.S. 1987. Meteorological operations at Cape Hatt in support of the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):42-50.
NUMMEDAL, D. 1979. Persistence of spilled oil on the Beaufort Sea Coast. Final Report, National Oceanic and Atmospheric Administration-OCSEAP Contract 03-5022-82, Research Unit 540. 48 p.
OWENS, E.H. 1971. The restoration of beaches contaminated by oil in Chedabucto Bay, Nova Scotia. Ottawa: Department of Energy, Mines and Resources, Marine Sciences Branch. Manuscript Report Series No. 19. 75 p.
______. 1978. Mechanical dispersal of oil stranded in the littoral zone. Journal Fisheries Research Board Canada 35(5):563-572.
______. 1984a. Shoreline countermeasures — 1983 study results. Baffin Island Oil Spill (BIOS) Project Working Report 83-4. Ottawa: Environmental Protection Service, Environment Canada. 102 p.
______. 1984b. Variability in estimates of oil contamination in the intertidal zone on a gravel beach. Marine Pollution Bulletin 15(11):412-416.
______. 1985. Factors affecting the persistence of stranded oil on low energy coasts. Proceedings 1985 Oil Spill Conference. Washington, D.C.: American Petroleum Institute Pub. No. 4385. 359-365.
______ 1987. Estimating and quantifying oil contamination on the shoreline. Marine Pollution Bulletin 18(3):110-118.
______ and RASHID, M. 1976. Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia. Canadian Journal of Earth Sciences 13(7):908-928.
OWENS, E.H., and HARPER, J.R. 1977. Frost table and thaw depth in the littoral zone near Peard Bay, Alaska. Arctic 30:154-168.
OWENS, E.H., and ROBSON, W. 1987. Experimental design and the retention of oil on arctic test beaches. Arctic 40 (Supp. 1):230-243.
OWENS, E.H., HARPER, J.R., and FOGET, C.R. 1982. Shoreline countermeasures — 1981 study results. Baffin Island Oil Spill (BIOS) Project Working Report 81-4. Ottawa: Environmental Protection Service, Environment Canada. 123 p.
______. 1983. Shoreline countermeasures — 1982 study results. Baffin Island Oil Spill (BIOS) Project Working Report 82-4. Ottawa: Environmental Protection Service, Environment Canada. 129 p.
OWENS, E.H., HOPE, D., and HUMPHREY, B. 1986a. 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, Unpubl. Report No. EE-84, River Road Technology Centre, Ottawa. 98 p.
OWENS, E.H., ROBSON, W., and HUMPHREY, B. 1986b. Data on the character of asphalt pavements. Proceedings of 9th Arctic Marine Oilspill Program (AMOP) Technical Seminar, June 10-12, Edmonton, Alberta. 1-17.
______, HOPE, D., and HARPER, J.R. 1987a. The fate of stranded oil four years after an experimental spill on a sheltered gravel beach. Proceedings of 1987 Oil Spill Conference, April, Baltimore, MD. Washington, D.C.: American Petroleum (Institute) Pub. No. 4452:473-478.
OWENS, E.H., HUMPRHEY, B., and SERGY, G.A. 1987b. The migration of stranded oil from a sheltered beach into adjacent nearshore subtidal sediments. In: Kuiper, W.J., and Van den Brink, J., eds. Fate and Effects of Oil in Marine Ecosystems. Dordrecht, The Netherlands: Martinus Nijhoff Publishers BV. 231-241.
OWENS, E.H., ROBSON, W., and FOGET, C.R. 1987c. A field evaluation of selected beach-cleaning techniques. Arctic 40 (Supp. 1):244-257.
RASHID, M.A. 1974. Degradation of Bunker C oil under different coastal environments in Chedabucto Bay, Nova Scotia. Estuarine and Coastal Marine Science 2:137-144.
REED, M., SPAULDING, M.L., GUNDLACH, E.R., KANA, T.W., and SIAH, S.J. 1986. Formulation of a shoreline/oil spill interaction model. Proceedings of 9th Arctic Marine Oilspill Program (AMOP) Technical Seminar, June 10-12. Edmonton: Environment Canada. 77-100.
SEIP, K.L. 1984. The "Amoco Cadiz" oil spill — at a glance. Marine Pollution Bulletin 15(6):218-220.
SERGY, G.A., and BLACKALL, P.J. 1987. Design and conclusions of the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):1-9.
THOMAS, M.L.H. 1977. Long-term biological effects of Bunker-C in the intertidal zone. In: Wolfe, D.A., ed. Fate and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems. Oxford: Pergamon Press. 238-245.
TSOUK, E., AMIR, S., and GOLDSMITH, V. 1985. Natural self-cleaning of oil polluted beaches by waves. Marine Pollution Bulletin 16(1):11-19.
VANDERMEULEN, J.H. 1977. The Chedabucto Bay spill — "Arrow" 1970. Oceanus, 31-39.
______. 1982. Some conclusions regarding long-term biological effects of some major oil spills. Philosophical Transactions Royal Society London B297:335-357.

——— and GORDON, D.C. 1976. Re-entry of five-year-old stranded Bunker C fuel oil from a low-energy beach into the water, sediments and biota of Chedabucto Bay, Nova Scotia. Journal Fisheries Research Board Canada 33(9):2002-2010.

VANDERMEULEN, J.H., KEIZER, P.D., and PENROSE, W.R. 1977. Persistence of non-alkane components of Bunker C oil in beach sediments of Chedabucto Bay, and lack of their metabolism by molluscs. In: Proceedings 1977 Oil Spill Conference. Washington, D.C.: American Petroleum Institute. 469-482.