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The Fate of Chemically Dispersed and Untreated Crude Oil in Arctic Benthic Biota

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ABSTRACT. Subtidal benthic biota were monitored for petroleum hydrocarbons following two experimental oil spills at Cape Hatt, N.W.T., Canada. In one spill oil was chemically dispersed into the water column, and in the other oil was released onto the water surface and allowed to strand on the shoreline. In addition to baseline samples, samples were collected immediately after the oil releases, two to three weeks after and one and two years after. Initial observations did not distinguish between effects of the surface and dispersed releases. Total oil content and hydrocarbon compositional analyses were conducted to investigate patterns of uptake and depuration for five different arctic species: *Astarte borealis*, *Macoma calcarea*, *Mya truncata*, *Serripes groenlandicus* and *Strongylocentrotus droebachiensis*. Filter-feeding species took up oil rapidly from the water column, while deposit-feeding species took up oil less rapidly from the sediments. All species depurated most of the oil after one year, but after two years the deposit feeders appeared to be taking up more oil from sediments contaminated by stranded oil from the surface oil release.

Key words: oil, petroleum, determination, benthos, weathering, degradation, depuration, Arctic

RÉSUMÉ. On a recherché la présence d'hydrocarbures pétroliers dans le biote benthique sous le niveau des marées, à la suite de deux déversements expérimentaux de pétrole au cap Hatt (T. N.-O.), au Canada. Pour un des déversements, on a dispersé le pétrole chimiquement dans la colonne d'eau, et pour l'autre, on l'a répandu en nappe à la surface et on l'a laissé s'échouer sur le rivage. En plus des échantillons témoins, on a prélevé des échantillons tout de suite après les déversements, de deux à trois semaines plus tard, ainsi qu'un an et deux ans après. Lors des observations initiales, on n'a pas cherché à faire la différence entre les effets du déversement en surface et ceux du pétrole dispersé. On a fait des analyses de la teneur totale en hydrocarbures et de leur composition, pour étudier les mécanismes d'absorption et de dépuration de cinq espèces arctiques différentes: *Astarte borealis*, *Macoma calcarea*, *Mya truncata*, *Serripes groenlandicus* et *Strongylocentrotus droebachiensis*. Les espèces filtreuses ont absorbé rapidement le pétrole à partir de la colonne d'eau, tandis que les espèces dépositivores l'ont absorbé moins rapidement à partir des sédiments. Toutes les espèces ont rejeté la plupart du pétrole au bout d'un an, mais après deux ans, les espèces dépositivores semblaient encore absorber du pétrole à partir des sédiments pollués par le pétrole échoué provenant de la nappe déversée en surface.

Mots clés: pétrole, pétroliers, détermination, benthos, dégradation, décomposition, dépuration, arctiques

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INTRODUCTION

The Baffin Island Oil Spill (BIOS) Project assessed the use of chemical dispersants on an oil slick in the arctic nearshore by comparing the fate and effects of chemically (Corexit 9527) dispersed oil to the fate and effects of an untreated surface oil slick left to natural cleaning processes. Chemical dispersion has been used as an oil spill countermeasure to protect sensitive environments in temperate regions of the world (Nichols and Parker, 1985; Lindblom *et al.*, 1981). A study of dispersion effect and effectiveness was conducted in Searsport, Maine, around the time of the BIOS experiments (Gilfillan *et al.*, 1985). However the significance of the BIOS Project was the use of dispersants in the arctic environment.

The project rationale and design are described by Sergy and Blackall (1987). The experimental program was carried out at Cape Hatt, near the northern tip of Baffin Island, in Canada's eastern Arctic. This location is a typical eastern arctic ecosystem; physical, geochemical and biological settings are detailed elsewhere (Buckley *et al.*, 1987; Cretney *et al.*, 1987a,b,c; Snow *et al.*, 1987). The program continued for four years (1980-83). Baseline data were collected in the first year and two experimental oil releases each of approximately 15 m^3 of weathered (8% by volume) Lagomedio crude oil occurred in the second year. The first release was directly onto the water surface of a sheltered bay (Bay 11; see Fig. 1), and the second release, one week later, was of oil premixed with dispersant (10:1) into the water column of another bay (Bay 9; see Fig. 1) at depths from 3 to 10 m (Dickins *et al.*, 1987). This paper describes the fate of both the untreated and the dispersed oil in subtidal benthic marine animals.

The fate of the oil was also monitored in the water column (Humphrey *et al.*, 1987) and in the sediments (Boehm *et al.*, 1987). The effects of oil releases on the microbial communities (Bunch, 1987) and on the macrobenthos (Cross *et al.*, 1987a,b; Cross and Thomson, 1987) are also described elsewhere.

The benthic chemistry segment of the BIOS program examined the hydrocarbon content of a number of selected invertebrate species chosen from the local benthic community as sentinel (Phillips, 1980) organisms, but also found elsewhere in the Canadian Arctic (Thomson, 1982; Thomson *et al.*, 1987). The animals were analyzed for total oil content, and the oil from selected animals or composites was subjected to detailed compositional analysis to study its fate.

Many previous studies have examined the effects of oil on benthic invertebrates (e.g., Atlas *et al.*, 1978; Gilfillan and Vandermeulen, 1978; Percy, 1976). Various lethal and sublethal effects on arctic biota have been observed (see, for example, Wells and Percy, 1985; Rice *et al.*, 1984; Hutcheson and Harris, 1982), and it has been postulated (Elmgren *et al.*, 1983) that more than five years may be required for full recovery of communities exposed to oil even in temperate areas.

Some studies have compared the effects of dispersed and untreated oil on the benthos. Tjessem *et al.* (1984) studied the fate of dispersed crude oil in enclosed sea water containers (mesocosms) off the coast of Norway. They found high concen-

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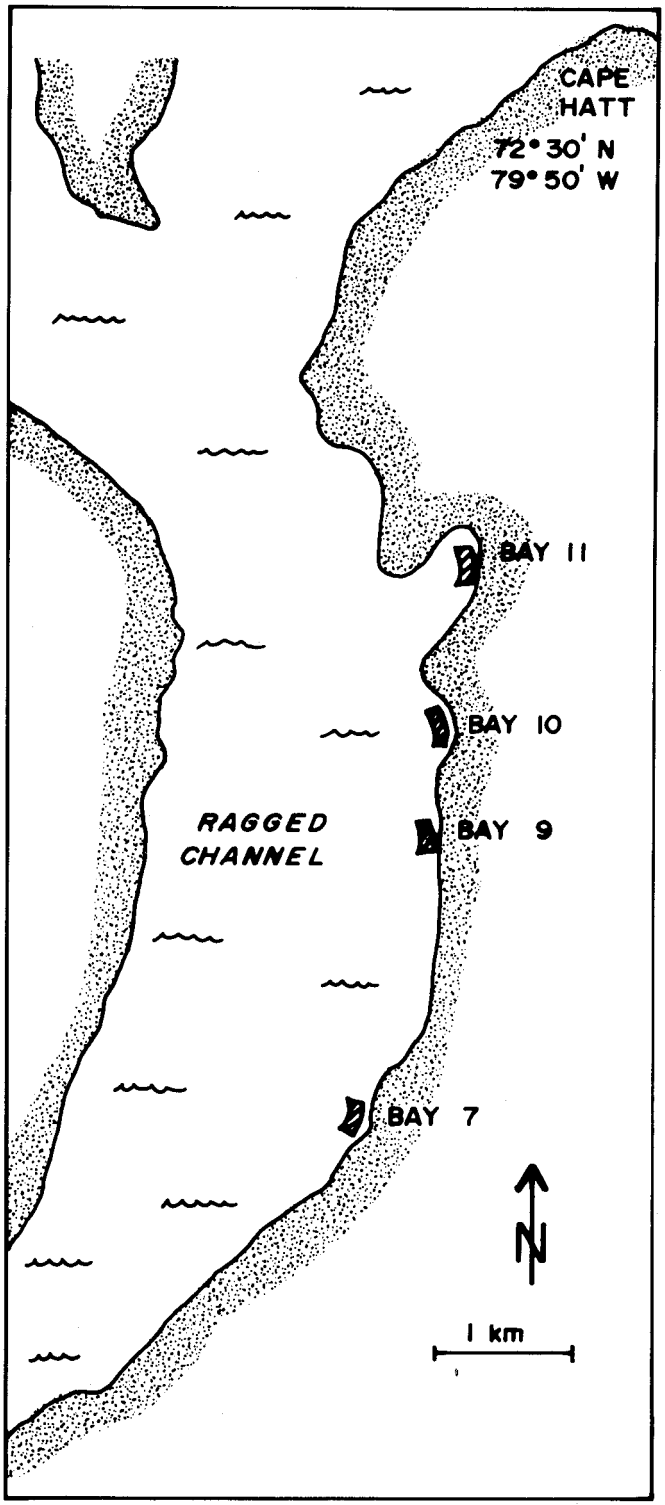

FIG. 1. Location of experimental bays at Cape Hatt, N.W.T. Bay 9 is the site of the dispersed oil release. Bay 11 is the site of the surface oil release.

trations of hydrocarbons (including the toxic polar and high molecular weight components) in the entire water column, but the biota were not monitored for hydrocarbon uptake. Farke *et al.* (1985) used mesocosm experiments to study the effects of dispersed oil on intertidal organisms. Chemical dispersion of the oil resulted in more retention of the lower molecular weight aromatic components and generally higher oil concentrations in the mesocosm systems. The concentration of hydrocarbons was not monitored in the biota, but sublethal effects were observed. Crothers (1983) reported on field observations of the effects of experimentally dispersed oil on the fauna and flora of rocky shores. Dispersed oil was found to have a larger impact (as measured by species survival and recolonization rates) than untreated oil. However, recovery was rapid in both cases, although slightly slower in winter than in summer.

Most studies of hydrocarbon accumulation and release by biota have been conducted in the laboratory; many of these studies were reviewed by Neff and Anderson (1981). Few have examined the concentrations and compositional changes (Gordon *et al.*, 1978) of petroleum hydrocarbons in animals exposed to oil. The 1981 dispersant effectiveness tests in Searsport, Maine, did monitor the hydrocarbon concentrations and compositions in two filter-feeding species, *Mya arenaria* and *Mytilus edulis*. Only those animals exposed to undispersed oil took up measurable amounts of oil, and hydrocarbon depuration was rapid (approximately one month) and complete.

The interdisciplinary BIOS Project provided an opportunity to examine all aspects of the fate of oil in benthic invertebrates over a long period of time. The results of the field studies are reported in this paper. Laboratory studies conducted in conjunction with the BIOS field experiments have also studied the uptake and depuration of oil dispersed in the water column by arctic invertebrates (Mageau *et al.*, 1987) and are reported elsewhere in this journal.

METHODS

Sentinel animals were chosen from the *Macoma* community, a widespread and common feature of the High Arctic nearshore. This community includes the bivalve species selected for this experiment: *Macoma calcarea* (CAL), *Mya truncata* (TRU), *Astarte borealis* (BOR) and *Serripes groenlandicus* (GRO). In addition an urchin, *Strongylocentrotus droebachiensis* (DRO), a common grazer, was selected. These animals include filter feeders (BOR, TRU and GRO) and deposit feeders (CAL and DRO). Differences in oil uptake between filter and deposit feeders have been observed in other locations by Roesijadi *et al.* (1978), where the oil contamination was in the sediments rather than the water column.

The sampling strategy was determined by the baseline biological study (Cross *et al.*, 1987a,b; Cross and Thomson, 1987) and is discussed in detail by Cretney *et al.* (1987c). Biota samples were collected for hydrocarbon analysis from specific tissue plots (see Fig. 2) at two water depth strata in each bay. Sediment samples were collected from the same plots for hydrocarbon analysis by methods similar to those used for the tissue hydrocarbon analyses. There were five tissue plots per depth stratum, situated adjacent to the biological study areas (benthic transects; see Fig. 2). The monitoring program included four bays (Bays 7, 9, 10 and 11; see Fig. 1) and five sampling periods (1980, 1981a, 1981b, 1982 and 1983). Specifically, sediment and biota samples from all bays were collected and analyzed in 1980 and 1981 to determine baseline conditions (Cretney *et al.*, 1987a,c). Samples were also collected from Bay 11 (the site of the surface release on 19 August 1981) one day after that release (1981a). Samples were collected from the other bays one or two days after the dispersed oil release (also 1981a) that took place on 27 August 1981 in Bay 9. Bay 10 was intended to be used as a

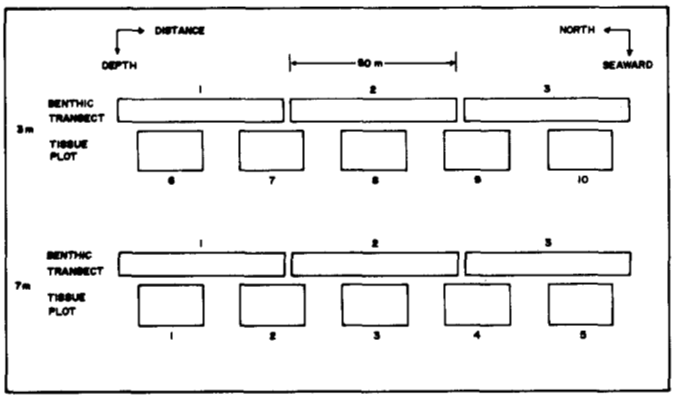

FIG. 2. Biota sampling locations in experimental bays.

control but was contaminated by the spill in Bay 9; Bay 7 was therefore used as a control from 1981 on. Sediment and biota in all bays were resampled two weeks after the dispersed oil release (1981b) and again in 1982 and 1983. Not all designated samples were collected or analyzed in later sampling periods. For example, samples were not collected from any of the 3 m strata tissue plots in 1982 and 1983 or from Bay 10 in 1983 to focus the analytical effort. By the end of the project, a set of results for five species from four bays at 7 m depth and five sampling periods (four periods for Bay 10) was available for detailed statistical analysis.

Animals were collected by divers. Most animals were collected by an airlift method (Snow *et al.*, 1987), except for urchins and some *S. groenlandicus*, which were hand-picked. A minimum of ten animals of each species was taken from each plot. After collection, the animals were wrapped in aluminum foil, bagged and frozen until analysis.

Details of the analytical procedures are given in the BIOS working reports (Boehm, 1981, 1982, 1983; Boehm *et al.*, 1984). Hydrocarbons were extracted from the tissue samples and the oil contents of the extracts determined by ultraviolet/fluorescence (UV/F) spectroscopy. Extract composites were also examined by gas chromatography with flame ionization (GC/FID) and mass spectrometric (GC/MS) detection to determine hydrocarbon compositions.

The extraction scheme is based on that of Warner (1976). Animals were thawed just prior to analysis. Tissue was removed from the shell or exoskeleton with solvent-cleaned utensils and homogenized to produce a composite sample from the whole tissues of at least ten animals. A subsample was used for wet weight/dry weight determination. Internal standards were added to the remainder, which was digested overnight with 10 ml of 5N KOH. The digest was extracted with hexane, which was then dried and reduced in volume to about 1 ml by rotary evaporation. Prior to UV/F analysis, the extracts were eluted through an alumina column with 9:1 hexane:dichloromethane to remove interfering polar and biogenic compounds. The eluate volume was reduced to about 2.5 ml.

The UV/F analysis is based on methods developed by Lloyd (1971a,b,c) and later used by Wakeham (1977) and Boehm *et al.* (1982). The method relies on the separation of emission peaks of multi-ring aromatics when the emission and excitation wavelengths are scanned simultaneously with a set wavelength separation. When scanned with a separation of 25 nm, Lagomedio crude oil shows a peak at 325 nm excitation wavelength and 350 nm emission wavelength. This peak was used as the identifier for the experimental oil. Oil concentrations were determined by comparing sample extract peak heights to standard peak heights from a curve derived from Lagomedio crude oil. Results are reported as Lagomedio equivalents.

Data from the UV/F analyses were evaluated statistically. Data were log transformed and all statistical analyses carried out on log data. Log transformation provided a data set with quite homogeneous variances, thus permitting statistical analysis of the results. To determine equivalency of means from two sets of five analyses, Student's t for a two-group comparison was determined and compared to t from a table, based on 95% probability. An F test, again at 95% probability, was performed when more than two sets of sample means appeared to be equivalent.

Extract composites for UV/F analysis were subsequently analyzed by capillary gas chromatography (Cretney *et al.*, 1987c). Extracts were fractionated by elution through a column packed with 11 g 100% activated silica gel, 1 g 5% deactivated alumina and 1 g copper. The sample was placed on the column, eluted first with hexane to remove the non-polar aliphatic compounds (F1), followed by 1:1 dichloromethane:hexane to remove the polar aromatic components (F2).

The aliphatic F1 fraction was analyzed by capillary GC/FID. The aromatic F2 fraction was analyzed by GC/MS using the selected ion monitoring technique (SIM) to determine concentrations of selected aromatic hydrocarbons. Procedural details are given in the BIOS working reports (Boehm, 1982, 1983; Boehm *et al.*, 1984).

A set of weathering indexes determined for each sample analyzed by GC/FID or GC/MS was used to aid in interpretation of the results.

RESULTS

The results of the UV/F analyses of the tissue samples from Bays 11, 10, 9 and 7 are reported in Tables 1-4. Results are presented graphically in Figure 3 and represent baseline sampling, two post-release samplings in 1981 and samplings in 1982 and 1983 (except for Bay 10). An important point regarding sampling periods is that in Bay 11, the 1981a period occurred after the surface release in that bay, but before the dispersed release in Bay 9. For all other bays, the 1981a sampling period occurred just after the dispersed oil release. The 1981b sampling period occurred in all bays two weeks after the dispersed oil release and three weeks after the surface release.

The levels of exposure to dispersed oil experienced by the animals in Bays 7, 9 and 10 were calculated from measured water column oil concentrations (Humphrey *et al.*, 1987). These results are presented in Table 5.

Comparisons were made between oil contents of airlifted and hand-picked *S. groenlandicus* samples and between samples from the two depth strata (Boehm, 1982). No differences were observed between the two sampling methods, but animals from the 3 m stratum usually contained slightly more oil than those from the 7 m stratum. The 3 m stratum was discarded after 1981 to focus the analytical effort, as animals were less abundant at that depth.

Baseline data indicate considerable inter-species and inter-bay variability, although all baseline data are low compared to post-release levels. Some differences that stand out are the relatively high baseline oil equivalent levels in *A. borealis* and *M. calcarea* from Bay 7 and the generally high oil equivalent levels in *S. droebachiensis* from all bays.

TABLE 1. UV/F analysis of oil content of Bay 11 tissues

Animal	Bay	Year	Number of plots	Log transformed data: Mean	Log transformed data: Standard deviation	Geometric mean ($\mu g \cdot g^{-1}$)
BOR	11	Baseline	5	–0.38	.29	0
BOR	11	1981A	5	0.43	.08	3
BOR	11	1981B	4	2.15	.28	140
BOR	11	1982	5	1.57	.04	37
BOR	11	1983	5	1.18	.45	15
CAL	11	Baseline	4	0.33	.50	2
CAL	11	1981A	5	1.39	.19	24
CAL	11	1981B	4	2.39	.32	250
CAL	11	1982	5	1.78	.15	60
CAL	11	1983	5	1.80	.16	64
TRU	11	Baseline	5	–0.37	.08	0
TRU	11	1981A	5	0.28	.17	2
TRU	11	1981B	5	1.97	.09	93
TRU	11	1982	5	0.12	.13	1
TRU	11	1983	5	0.58	.42	4
GRO	11	Baseline	1			11
GRO	11	1981A	4	0.73	.60	5
GRO	11	1981B	3	2.59	.19	390
GRO	11	1982	4	1.11	.24	13
GRO	11	1983	5	1.04	.19	11
DRO	11	Baseline	5	1.10	.27	13
DRO	11	1981A	5	1.89	.70	78
DRO	11	1981B	5	2.63	.47	430
DRO	11	1982	5	1.66	.17	46
DRO	11	1983	5	2.01	.26	100

1981A: after surface release, before dispersed release, Bay 11 only 1981-08-21.
1981B: 1981-09-08.
BOR: *A. borealis*.
CAL: *M. calcarea*.
TRU: *M. truncata*.
GRO: *S. groenlandicus*.
DRO: *S. droebachiensis*.

TABLE 2. UV/F analysis of oil content of Bay 10 tissues

Animal	Bay	Year	Number of plots	Log transformed data: Mean	Log transformed data: Standard deviation	Geometric mean ($\mu g \cdot g^{-1}$)
BOR	10	Baseline	5	–0.38	.16	0
BOR	10	1981A	4	2.56	.03	360
BOR	10	1981B	5	2.49	.14	310
BOR	10	1982	5	1.40	.08	25
CAL	10	Baseline	5	0.29	.23	2
CAL	10	1981A	5	2.61	.18	410
CAL	10	1981B	4	2.72	.09	520
CAL	10	1982	5	1.14	.09	14
TRU	10	Baseline	5	–0.25	.10	1
TRU	10	1981A	5	2.44	.14	280
TRU	10	1981B	5	2.20	.13	160
TRU	10	1982	5	–0.02	.12	1
GRO	10	Baseline	5	0.10	.30	1
GRO	10	1981A	5	2.51	.08	320
GRO	10	1981B	4	2.15	.06	140
GRO	10	1982	5	0.47	.07	3
DRO	10	Baseline	5	1.28	.34	19
DRO	10	1981A	5	1.95	.11	89
DRO	10	1981B	5	2.03	.13	110
DRO	10	1982	5	1.31	.10	20

1981A: 2 days after dispersed release, 1981-08-29.
1981B: 1981-09-11.
BOR: *A. borealis*.
CAL: *M. calcarea*.
TRU: *M. truncata*.
GRO: *S. groenlandicus*.
DRO: *S. droebachiensis*.

TABLE 3. UV/F analysis of oil content of Bay 9 tissues

Animal	Bay	Year	Number of plots	Log transformed data: Mean	Log transformed data: Standard deviation	Geometric mean ($\mu g \cdot g^{-1}$)
BOR	9	Baseline	4	–0.10	.16	1
BOR	9	1981A	5	2.66	.19	460
BOR	9	1981B	5	2.23	.23	170
BOR	9	1982	5	1.28	.26	19
BOR	9	1983	5	0.84	.10	7
CAL	9	Baseline	5	–0.15	.22	1
CAL	9	1981A	5	1.87	.25	75
CAL	9	1981B	5	2.92	.11	840
CAL	9	1982	5	1.40	.13	25
CAL	9	1983	5	1.10	.27	13
TRU	9	Baseline	5	–0.47	.15	0
TRU	9	1981A	5	2.08	.30	120
TRU	9	1981B	5	2.06	.08	110
TRU	9	1982	5	–0.09	.20	1
TRU	9	1983	5	0.47	.25	3
GRO	9	Baseline	5	–0.33	.45	0
GRO	9	1981A	5	2.40	.14	250
GRO	9	1981B	5	1.98	.17	96
GRO	9	1982	5	0.71	.10	5
GRO	9	1983	5	0.01	.24	1
DRO	9	Baseline	5	1.20	.15	16
DRO	9	1981A	5	1.65	.11	45
DRO	9	1981B	5	2.33	.20	220
DRO	9	1982	5	1.67	.22	46
DRO	9	1983	5	2.18	.25	150

1981A: 1981-08-28.
1981B: 1981-09-10.
BOR: *A. borealis*.
CAL: *M. calcarea*.
TRU: *M. truncata*.
GRO: *S. groenlandicus*.
DRO: *S. droebachiensis*.

If Bay 11 (surface oil release) data are disregarded, two predominant patterns emerge from the results. For the filter feeders *A. borealis* and *S. groenlandicus*, oil concentrations increased immediately after the dispersed oil release and began to decrease by the next sampling, continuing to decrease the following years. The filter feeder *M. truncata* also follows this pattern except that an increase is observed in 1983. For the deposit feeders *M. calcarea* and *S. droebachiensis*, the increase occurred more gradually over the two 1981 sampling periods, decreased in 1982 and increased again in 1983. An exception to this pattern is seen for *M. calcarea* in Bay 9, in which the increase in 1983 is not observed.

The data plotted in Figure 3 can be used to make an inter-bay comparison of the uptake/depuration responses of the species studied. The filter feeder response was more dramatic in Bay 7 animals than in those from Bays 9 and 10. Bay 7 filter feeders showed rapid uptake and depuration of the oil, while those in Bays 9 and 10 rapidly took up oil but depurated it more gradually. The deposit feeder response was similar among Bay 9 and 10 animals, while those in Bay 7 took up less oil and depurated it to lower levels.

The data for Bay 11 (Table 1; Fig. 3a) indicate that a small increase in oil concentration occurred in all animals after the surface oil release in that bay (1981a), but that increase was minor compared to the increases observed after the dispersed oil release in Bay 9 (1981b). Later samplings (1982, 1983) indicate that the oil concentrations remain generally higher in Bay 11 animals than in those in other bays.

TABLE 4. UV/F analysis of oil content of Bay 7 tissues

Animal	Bay	Year	Number of plots	Log transformed data: Mean	Log transformed data: Standard deviation	Geometric mean ($\mu g \cdot g^{-1}$)
BOR	7	Baseline	4	0.31	.32	2
BOR	7	1981A	5	1.70	.52	50
BOR	7	1981B	4	1.75	.26	56
BOR	7	1982	5	0.83	.27	7
BOR	7	1983	5	0.22	.44	2
CAL	7	Baseline	5	0.02	.06	1
CAL	7	1981A	5	1.91	.11	82
CAL	7	1981B	5	1.93	.27	85
CAL	7	1982	5	0.28	.07	2
CAL	7	1983	5	0.72	.41	5
TRU	7	Baseline	5	−0.48	.13	0
TRU	7	1981A	5	2.06	.21	110
TRU	7	1981B	5	1.67	.14	47
TRU	7	1982	5	−0.38	.13	0
TRU	7	1983	5	0.04	.15	1
GRO	7	Baseline	3	0.04	.07	1
GRO	7	1981A	4	2.71	.10	520
GRO	7	1981B	3	1.88	.28	75
GRO	7	1982	5	0.33	.16	2
GRO	7	1983	5	0.32	.63	2
GRO	7	1983	4	0.06	.29	1
DRO	7	Baseline	5	1.09	.12	12
DRO	7	1981A	5	1.66	.12	46
DRO	7	1981B	5	1.62	.13	42
DRO	7	1982	5	0.78	.24	6
DRO	7	1983	5	1.09	.28	12

1981A: 1981-09-01.
1981B: 1981-09-11.
BOR: *A. borealis*.
CAL: *M. calcarea*.
TRU: *M. truncata*.
GRO: *S. groenlandicus*.
DRO: *S. droebachiensis*.

Gas chromatographic analysis of the F1 alkane and F2 aromatic fractions of the tissue extracts provided information on their hydrocarbon composition. The presence of petrogenic material could be detected, and its degree of weathering and biodegradation was estimated through a qualitative examination of the chromatograms and evaluation of the weathering indexes described in Table 6. Unoiled tissues contain significant quantities of biogenic hydrocarbons originating from planktonic material (nC_{17} and pristane) and terrigenous plant materials (odd carbon chain normal alkanes C_{25} through C_{33}). The presence of oil in the F1 aliphatic fraction is indicated by phytane and a series of odd and even carbon number *n*-alkanes. The presence of oil in the F2 aromatic fraction is indicated by the presence of alkylated naphthalenes, phenanthrenes and dibenzothiophenes. Loss of low molecular weight aliphatic components (both normal and branched alkanes) followed by loss of low molecular weight aromatics (the naphthalene compound series) was taken as indication of weathering. Two ratios of normal alkanes to isoprenoid alkanes (*n*-alkanes/isoprenoids and nC_{18}/phytane; see Table 6) are used to estimate the extent of biodegradation of the oil. Aromatic fraction degradation was indicated by the dominance of alkylated phenanthrenes and dibenzothiophenes in the aromatic fraction. The presence of unresolved complex mixture (UCM) in the F1 fraction was used as an indicator of degraded oil.

Results of the gas chromatographic analyses of tissue extracts from Bay 11, 10, 9 and 7 animals are summarized in Tables 7-10. Note that a somewhat subjective interpretation of the chromatographic patterns is also offered in these tables. Complete sets of chromatograms (GC/FID of the F1 aliphatic and F2 aromatic fractions, GC/MS of the F2 fractions) have been reported in the BIOS working reports (Boehm, 1981, 1982, 1983; Boehm *et al.*, 1984; Engelhardt and Norstrom, 1982). Representative chromatograms and aromatic distributions are shown in Figure 4 and discussed below.

The results of the GC/FID analyses of the F1 aliphatic fractions of the tissues show general trends with some special cases. Immediately after the surface oil release in Bay 11, but before the dispersed oil release, the tissue extract chromatograms from Bay 11 biota did not indicate the presence of oil. Immediately after the dispersed oil release, however, chromatograms from most species from all bays indicate the presence of slightly weathered oil, similar to the released oil. Figure 4a is a typical chromatogram of the F1 fraction of this type of sample. The features of note are the resolvable *n*-alkanes from C_{12} to C_{30} and several isoprenoids. Special cases are *A. borealis* samples, which contain a more biodegraded oil than other species (as indicated by the near absence of *n*-alkanes less than C_{22} and an alkane/isoprenoid ratio of 0.1; see Tables 7-10), and *S. droebachiensis*, which do not appear to contain oil (as indicated by the absence of phytane).

By the second 1981 sampling period, relatively degraded oil was common in most tissue samples. A typical chromatogram of the F1 fraction of these samples is shown in Figure 4b. Note the loss of resolved *n*-alkanes along with the persistence of several isoprenoids and a significant UCM. These features are indicative of biodegradation, most likely occurring *in vivo*, as there is no evidence of such degradation occurring to any significant extent within this period in either the water or sediment (Boehm, 1982). *A. borealis* samples again contained a more biodegraded oil than the other species, and Bay 11 tissues contained the least weathered oil. *S. droebachiensis* samples again indicated low oil content.

Samples collected and analyzed in 1982 are all very similar to each other. A typical chromatogram of the F1 aliphatic fraction is shown in Figure 4c. A significant UCM and a large amount of pristane indicate the presence of heavily weathered oil. A new feature is present in many of the chromatograms: a suite of *n*-alkanes from C_{23} to C_{33} with a significant odd-even predominance. This feature is typical of terrigenous wax material, usually of plant origin. The decreased amount of oil in the 1982 tissues compared to the 1981 tissues (see data in Fig. 3) could account for the relative prominence of the terrigenous material in Figures 4c and 4d.

The *M. truncata* and the *S. groenlandicus* samples also contain some fresh oil, as indicated by the presence of low molecular weight alkanes (C_{14}-C_{20} range). The other filter feeder, *A. borealis*, did not show this low molecular weight material, but it could have degraded it more rapidly.

By 1983, the chromatograms of most samples display very few features that can be associated with the original oil. Figure 4d is a typical 1983 chromatogram of the F1 aliphatic fraction, with no identifiable C_{10}-C_{22} *n*-alkanes, significant amounts of pristane (a biogenic hydrocarbon) and a suite of terrigenous components in the C_{23}- C_{33} range. Bay 11 tissues, however, are an exception, as their chromatograms show significant petrogenic hydrocarbons even in 1983.

In general, GC/FID analyses of the F1 aliphatic fractions indicate that oil was taken up by the animals in all bays after the

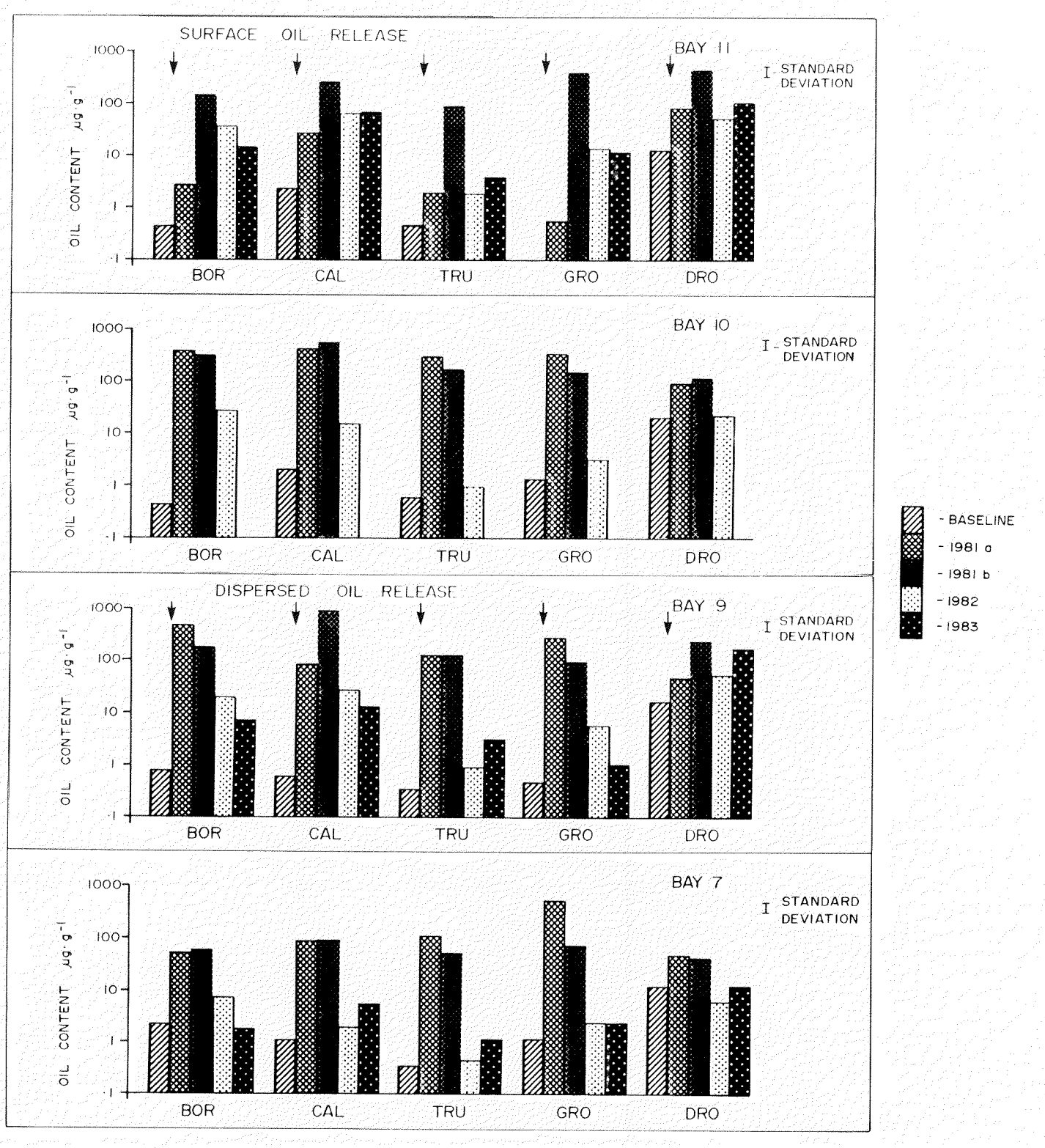

FIG. 3. Concentrations of oil in tissues by UV/F spectroscopy: a. Bay 11; b. Bay 10; c. Bay 9; d. Bay 7. BOR, *A. borealis*; CAL, *M. calcarea*; TRU, *M. truncata*; GRO, *S. groenlandicus*; DRO, *S. droebachiensis*. The data plotted are the geometric means of the results for one composite sample from each tissue plot. Up to five tissue plots were sampled in each bay (see Fig. 2 and Tables 1-4 for details). The indicated standard deviation therefore includes both sampling and analytical variability.

dispersed oil release. Oil began to be depurated and degraded immediately and continued to do so until no recognizable oil components remained after two years. After one year, some fresh oil appeared in the chromatograms along with degraded oil, but it was not in evidence after two years. Two features stand out in the results: biodegradation of aliphatics appears to occur *in vivo* in all species, but at a faster rate in *A. borealis* than in the other species, and *S. droebachiensis* does not appear to retain any oil.

GC/MS analyses of the tissue F2 aromatic fractions give

TABLE 5. Exposure levels

	Maximum* water column concentration ($mg \cdot l^{-1}$)	Exposure* $mg \cdot l^{-1} \cdot h$ (at 7 m)	*S. groenlandicus* body burden ($\mu g \cdot g^{-1}$) 1981A	1981B
Bay 9	160	300	250	96
Bay 10	1.2	30	320	140
Bay 7	0.1	1	520	75

*Humphrey *et al.*, 1987.

TABLE 6. Explanation of hydrocarbon weathering indexes

1. Alkane/Isoprenoid Ratio (Biodegradation)

$$\text{Alk/Iso} = \frac{nC_{14} + nC_{15} + nC_{16} + nC_{17} + nC_{18}}{\text{FARN} + \text{TM 13} + \text{NOR} + \text{PRIS} + \text{PHYT}}$$

This ratio approaches 0 as the *n*-alkanes are preferentially depleted.

2. nC_{18}/Phytane Ratio

This ratio approaches 0 as nC_{18} is preferentially depleted during biodegradation. This is a specific case of the Alk/Iso ratio.

3. Pristane/Phytane Ratio

Pristane occurs commonly in biota and in recent sediments as a degradation product of the phytol side chain of plant pigment chlorophyll, whereas phytane is not formed and is not commonly found in recent sediments; consequently, non-petroleum-derived hydrocarbons generally give rise to a high pristane/phytane ratio. The pristane/ phytane ratio has been used as an indicator of the presence or absence of petroleum. Although a high pristane/phytane ratio is generally a reliable indicator of the absence of petroleum, the converse is not necessarily true, that is, low values are less reliable indicators of the presence of petroleum hydrocarbons. Typical background values for this ratio are ~5, as reported by Boehm (1981).

4. Saturated Hydrocarbon Weathering Ratio (SHWR)

$$\text{SHWR} = \frac{\text{sum of } n\text{-alkanes from } nC_{12} \text{ to } nC_{25}}{\text{sum of } n\text{-alkanes from } nC_{17} \text{ to } nC_{25}}$$

The SHWR approaches 1.0 as low-boiling saturated hydrocarbons (nC_{12}-nC_{17}) are lost by evaporation.

5. Carbon Preference Index (CPI)

$$\text{CPI} = \frac{2(nC_{27} + nC_{29})}{nC_{26} + 2nC_{28} + nC_{30}}$$

CPI = 1.0 for petroleum

CPI ranges from 3 to 6 for terrigenous waxes, reflecting the formation mechanism for long chain hydrocarbons.

6. Aromatic Weathering Ratio

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

The AWR approaches 1.0 as low-boiling aromatics are lost by evaporation and/or dissolution.

similar generalized results. Immediately after the surface oil release in Bay 11, but before the dispersed oil release, tissue samples from Bay 11 species did not contain any aromatic oil compounds. Immediately after the dispersed oil release in Bay 9, biota from both Bays 9 and 10 contained fresh oil, as indicated by the abundance of naphthalene compounds (see Tables 7-10). A typical distribution of the aromatic component of these tissues is shown in Fig. 5a. Again the *S. droebachiensis* do not appear to contain significant concentrations of oil. Samples collected two weeks later in all bays indicate that oil degradation is proceeding. The aromatic distribution outlined in Fig. 5b shows the near absence of naphthalenes and a decrease in the concentration of phenanthrenes relative to the dibenzothiophenes. It is notable that *A. borealis* does not differ from other biota in the F2 fraction, although the *A. borealis* F1 fraction shows considerably more degradation at this sampling period.

In 1982, tissue F2 fractions are more typical of fresh oil than those from the end of 1981 (as indicated by the presence of the lower molecular weight naphthalenes; see Tables 7-10). In particular for *M. truncata*, *S. groenlandicus* and *S. droebachiensis*, naphthalenes dominate the aromatic distributions. There is an apparent contradiction in the *S. droebachiensis* results in that the animals appear to have taken up or retained only the aromatic components of the oil: the aliphatic fraction chromatograms did not show significant petrogenic hydrocarbon content. By 1983, no recognizable components from the original oil remain in most tissue samples except those from Bay 11.

Whole animal tissues were analyzed throughout this study. For practical reasons no attempt was made to estimate the effect of varying proportions of gut and tissue and of different tissue types in the samples. However, in 1981 both whole tissues and specific tissue parts of a large collection of *S. groenlandicus* from Bay 10 were analyzed to verify that the petrogenic hydrocarbons were contained in the animal tissue and not only in the gut. Little difference was observed between F1 fractions from the guts of the animals as compared to the rest of the tissue, but significant differences were observed when comparing the F2 fractions. Muscle tissue contained generally higher levels of lower molecular weight aromatics (the naphthalenes and alkylbenzenes), and generally lower levels of the higher molecular weight aromatics than the guts. However, these low molecular weight components are easily lost during the sample workup, and it is therefore difficult to make conclusions based on such differences when observed in only a small number of samples. Other sources of uncertainty are the influence of changes in species population on body burden data and the effects of differences in age structure, condition and life cycle stage of the organisms sampled from year to year. The magnitudes of these effects on the data are unknown.

DISCUSSION

Certain patterns appear from statistical analysis of the biota body burden data (Tables 1-4). Most obvious is the difference in initial hydrocarbon uptake between filter feeders and deposit feeders. Filter feeders picked up oil from the water column immediately after the dispersed oil release, with organisms from all bays giving similar results. Deposit feeders picked up hydrocarbon more slowly than filter feeders but had similar oil content by two weeks after the dispersed oil release. The pattern continues, with filter feeders and deposit feeders depurating oil over the first winter season, and with deposit feeders appearing to take up more oil over the following year, while filter feeders generally continue to depurate oil. Typically, the oil content of filter feeders increased by 1000 times in 1981 and was followed by reductions to $\frac{1}{10}$-$\frac{1}{100}$ of the maximum body burden of 1982 and another $\frac{1}{10}$ reduction to near baseline levels by 1983. Similar differences in oil uptake rates between filter feeders and deposit feeders have been observed in laboratory simulations of the BIOS field experiments (Mageau *et al.*, 1987).

Baseline results of the UV/F oil analysis are variable among

TABLE 7. Gas chromatographic results from Bay 11 tissues

Animal	Year	F1 (Aliphatic)	F2 (Aromatic)
BOR	1981A	No oil	No oil
	1981B	Moderate biodegradation up to nC_{20}; high UCM	No Ns; alkylated Ps and alkylated DBTs persist
	1982	Moderate biodegradation; high UCM	No Ns; alkylated Ps and alkylated DBTs persist
	1983	Low oil; moderate biodegradation up to nC_{20}; double UCM	Low alkylated Ps and alkylated DBTs only
CAL	1981A	No oil: CPI = 1.9	Low Ns and Ps; no DBTs
	1981B	Oil: CPI = 1; little biodegradation	No Ns; high Ps and DBTs
	1982	High oil; moderate biodegradation	No Ns; high Ps and DBTs
	1983	High oil; moderate biodegradation up to C_{20}; high isoprenoids and UCM	Low oil; alkylated Ps only
DRO	1981A	No oil: pris/phyt = 47	No oil
	1981B	Low oil: pris/phyt = 10	Low oil: some Ns, Ps and DBTs
	1982	Biodegraded: C_{18}/phyt = 0.1	Ns and Ps dominate
	1983	More oil; biodegradation up to nC_{20}; high UCM and phytane	High alkylated P; no DBTs
GRO	1981A	No oil	No oil
	1981B	Little biodegradation up to C_{22}	Little degradation: no Ns, high alkylated P and alkylated DBTs
	1982	Low new *n*-alkanes C_{10}-C_{22}; UCM	Ns dominate; little DBTs and Ps
	1983	More oil; biodegraded up to C_{20}; high UCM	Low alkylated Ns and P, no DBTs
TRU	1981A	No oil	No oil
	1981B	Little biodegradation: loss of *n*-alkanes	Little weathering: high alkylated P, alkylated DBT and UCM
	1982	New *n*-alkanes C_{10}-C_{22}; high UCM and isoprenoids	Moderate oil; Ps and DBTs dominate
	1983	Low oil: pris/phyt = 14; some new oil: C_{18}/phyt = 1.0; high UCM	Low oil; alkylated Ns dominate

BOR = *Astarte borealis*.
CAL = *Macoma calcarea*.
DRO = *Strongylocentrotus droebachiensis*.
GRO = *Serripes groenlandicus*.
TRU = *Mya truncata*.
N = naphthalene.
Ns = naphthalene compound series.
P = phenanthrene.
Ps = phenanthrene compound series.
DBT = dibenzothiophene.
DBTs = dibenzothiophene compound series.
UCM = unresolved complex material.
C_{18}/phyt = nC_{18}/phytane ratio (see Table 6).
pris/phyt = pristane/phytane ratio (see Table 6).
CPI = carbon preference index (see Table 6).

TABLE 8. Gas chromatographic results from Bay 10 tissues

Animal	Year	F1 (Aliphatic)	F2 (Aromatic)
BOR	1981A	Moderate biodegradation: alk/iso = 1.3	High Ns, Ps and DBTs
	1981B	High biodegradation up to nC_{20}; alk/iso = 0.1	High oil; loss of Ns only
	1982	Very low oil	Ps and DBTs persist
	1983	N.A.	N.A.
CAL	1981A	High oil; CPI = 1	N.A.
	1981B	Little biodegradation; C_{18}/phyt = 0.7	N.A.
	1982	Less oil, moderate degradation	No Ns; alkylated P and alkylated DBT dominate
	1983	N.A.	N.A.
DRO	1981A	No oil: pris/phyt = 42	No oil
	1981B	Low oil: pris/phyt = 18	Low oil: low Ns, Ps and DBTs
	1982	Low oil	Low oil; Ps dominate
	1983	N.A.	N.A.
GRO	1981A	Fresh oil	Fresh oil: high Ns, Ps, DBTs
	1981B	Little biodegradation up to nC_{22}; double UCM	Ps, DBTs and alkylated N persist
	1982	Low new *n*-alkanes C_{10}-C_{22}; some UCM	Alkylated N and alkylated P persist; low DBTs
	1983	N.A.	N.A.
TRU	1981A	Fresh oil	Fresh oil: high Ns, Ps, DBTs
	1981B	Loss of *n*-alkanes; isoprenoids and UCM persist	Less oil; loss of Ns, P, DBTs; alkylated P, alkylated DBT and UCM persist
	1982	Less oil; new *n*-alkanes C_{10}-C_{22}; high UCM	Less oil; new Ns dominate
	1983	N.A.	N.A.

BOR = *Astarte borealis*.
CAL = *Macoma calcarea*.
DRO = *Strongylocentrotus droebachiensis*.
GRO = *Serripes groenlandicus*.
TRU = *Mya truncata*.
N.A. = not analyzed.
N = naphthalene.
Ns = naphthalene compound series.
P = phenanthrene.
Ps = phenanthrene compound series.
DBT = dibenzothiophene.
DBTs = dibenzothiophene compound series.
UCM = unresolved complex material.
C_{18}/phyt = nC_{18}/phytane ratio (see Table 6).
pris/phyt = pristane/phytane ratio (see Table 6).
alk/iso = *n*-alkane/isoprenoid ratio (see Table 6).
CPI = carbon preference index (see Table 6).

TABLE 9. Gas chromatographic results from Bay 9 tissues

Animal	Year	F1 (Aliphatic)	F2 (Aromatic)
BOR	1981A	Moderate weathering up to C_{14}; alk/iso = 2.0	High Ns, Ps and DBTs
	1981B	High biodegradation up to C_{22}; alk/iso = 0.2	Less oil; loss of N; Ps and DBTs persist
	1982	Low oil	Low alkylated P and alkylated DBT
	1983	Low oil; biodegradation up to C_{20}; double UCM	Low alkylated P only
CAL	1981A	Low oil: CPI = 1.3; C_{18}/phyt = 1.7	High Ns, Ps and DBTs
	1981B	More oil: CPI = 1; little biodegradation; C_{18}/phyt = 0.8	More oil; no compositional changes
	1982	Moderate degradation	No Ns; alkylated P and alkylated DBT dominate
	1983	Low oil; low phytane and UCM	P dominant
DRO	1981A	No oil: pris/phyt = 121	Some Ns, Ps and DBTs
	1981B	Low oil: pris/phyt = 21	High Ps and DBTs
	1982	More oil: phytane, *n*-alkanes, moderate degradation: some UCM	Low DBTs; some Ps
	1983	Low oil; high UCM only	No oil
GRO	1981A	Fresh oil: *n*-alkanes down to C_{10}	Fresh oil: high Ns, P, DBTs
	1981B	Little biodegradation up to nC_{22}; double UCM	No Ns; Ps and DBTs persist
	1982	Less oil; new *n*-alkanes C_{10}-C_{22}; small UCM	Little degradation: N dominate
	1983	No oil	No oil
TRU	1981A	Fresh oil: *n*-alkanes down to C_{10}	Fresh oil: high Ns, Ps, DBTs
	1981B	Loss of *n*-alkanes; isoprenoids and UCM persist	Loss of Ns, P, DBT; alkylated P, alkylated DBT and UCM persist
	1982	Less oil; new *n*-alkanes C_{10}-C_{22}; high UCM; C_{18}/phyt = 0.6	Less oil; new Ns dominate
	1983	No oil: pris/phyt = 50	No oil

BOR = *Astarte borealis*.
CAL = *Macoma calcarea*.
DRO = *Strongylocentrotus droebachiensis*.
DBT = dibenzothiophene.
GRO = *Serripes groenlandicus*.
TRU = *Mya truncata*.
N = naphthalene.
Ns = naphthalene compound series.
P = phenanthrene.
Ps = phenanthrene compound series.
DBT = dibenzothiophene.
DBT = dibenzothiophene.
DBTs = dibenzothiophene compound series.
UCM = unresolved complex material.
C_{18}/phyt = nC_{18}/phytane ratio (see Table 6).
pris/phyt = pristane/phytane ratio (see Table 6).
alk/iso = *n*-alkane/isoprenoid ratio (see Table 6).
CPI = carbon preference index (see Table 6).

TABLE 10. Gas chromatographic results from Bay 7 tissues

Animal	Year	F1 (Aliphatic)	F2 (Aromatic)
BOR	1981A	High biodegradation up to nC_{20}; alk/iso = 0.2	Little degradation: low Ns, moderate Ps, DBTs
	1981B	High biodegradation	Little depuration; no N, moderate P, DBTs
	1982	No oil	No oil
	1983	Low oil: biodegradation up to C_{20}; double UCM	Alkyl N, alkyl P, and alkyl DBTs
CAL	1981A	Low oil: CPI = 1.3; no degradation	N.A.
	1981B	No new oil: CPI = 1.3; biodegradation, C_{18}/phyt = 0.4	Low oil; weathered: only alkyl P and alkyl DBTs
	1982	No oil	Low Ps only
	1983	Low oil; low UCM and phytane	Alkyl N and alkyl P only
DRO	1981A	No oil: pris/phyt = 97	No oil
	1981B	Low oil: pris/phyt = 54	No oil
	1982	No oil	Low oil; Ns dominate
	1983	Low oil; low UCM and phytane	Low P only
GRO	1981A	Moderate biodegradation, alk/iso = 0.2	Little degradation: low Ns; high Ps and DBTs
	1981B	Less oil; little degradation	Less oil; little degradation
	1982	New *n*-alkanes C_{10}-C_{22}, low UCM	Low N, no DBTs; Ps dominate
	1983	No oil	No oil
TRU	1981A	Little biodegradation: low C_{18}/phyt	Low oil; moderate degradation: low Ns, low UCM
	1981B	Less oil; more biodegradation	Less oil; no Ns, less Ps, DBTs
	1982	Less oil; new *n*-alkanes C_{10}-C_{22}; high UCM	Less oil; new Ns dominate
	1983	Low oil; low UCM and low phytane	Low oil: only low alkyl N present

BOR = *Astarte borealis*.
CAL = *Macoma calcarea*.
DRO = *Strongylocentrotus droebachiensis*.
GRO = *Serripes groenlandicus*.
TRU = *Mya truncata*.
N.A. = not analyzed.
N = naphthalene.
Ns = naphthalene compound series.
P = phenanthrene.
Ps = phenanthrene compound series.
DBT = dibenzothiophene.
DBTs = dibenzothiophene compound series.
UCM = unresolved complex material.
C_{18}/phyt = nC_{18}/phytane ratio (see Table 6).
pris/phyt = pristane/phytane ratio (see Table 6).
alk/iso = *n*-alkane/isoprenoid ratio (see Table 6).
CPI = carbon preference index (see Table 6).

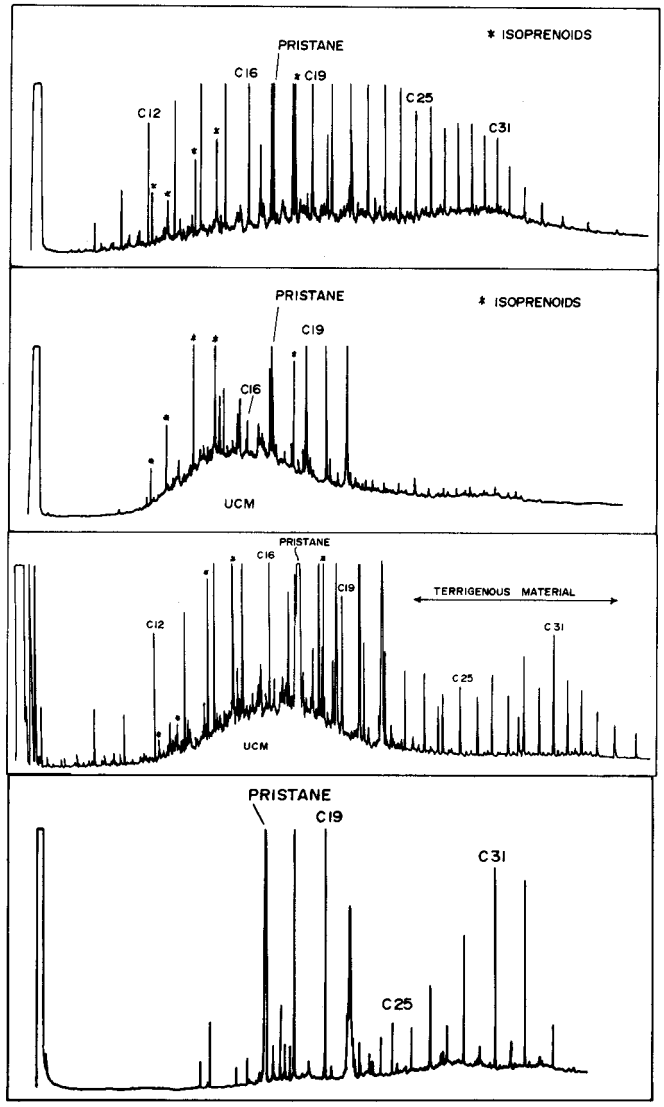

FIG. 4. Gas chromatogram (GC/FID) of the F1 aliphatic fraction of typical tissue extracts. a: Sample collected immediately after the dispersed oil release. b: Sample collected two weeks after the dispersed oil release (1981b). c: Sample collected one year after the experimental oil releases (1982). d: Sample collected two years after the experimental oil releases (1983).

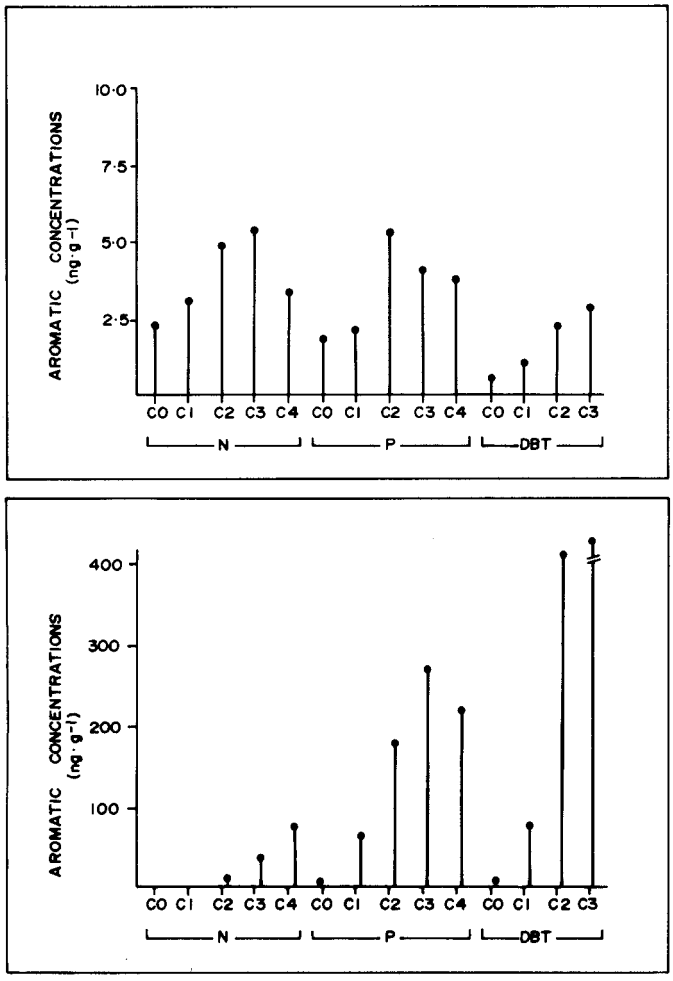

FIG. 5. Distribution of aromatic hydrocarbons in tissues. a: Sample collected immediately after the dispersed oil release. b: Sample collected two weeks after the dispersed oil release. N, naphthalenes; P, phenanthrenes; DBT, dibenzothiophenes; C_n indicates the number of carbon atoms in the alkyl side chain attached to the parent N, P or DBT compound.

species. These hydrocarbon content differences have been examined by Cretney *et al.* (1987c), who have related them in part to differences in feeding patterns. An interesting result was obtained for *S. droebachiensis:* they have a high oil equivalent content (UV/F method; see data in Tables 1-4) in baseline data, but this is not confirmed by GC methods, which show an absence of petrogenic hydrocarbons. No explanation for this was found.

The correspondence between UV/F oil analysis results and gas chromatographic compositional observations decreased with time. The correspondence was good at high hydrocarbon concentrations and with oil in a similar state of weathering as the original Lagomedio oil (Boehm, 1981, 1982). By 1982, with oil concentrations decreasing, the GC/FID results for the F1 fractions underestimated oil concentrations in comparison to the UV/F results (Boehm, 1983; Boehm *et al.*, 1984). This is not surprising, as GC methods are specific for relatively low molecular weight hydrocarbons, while the UV/F method is sensitive to a wider range of molecular weights and is not specific to hydrocarbons but is sensitive to substituted polar compounds as well. Recent studies suggest that the UV/F spectrum is not significantly changed even after extensive weathering (Humphrey and Vandermeulen, 1986). It is likely that the UV/F method is more robust over time than the GC methods and that UV/F results from this study do indicate the presence of persistent Lagomedio oil, although the oil composition has changed. The UV/F determination may be sensitive to weathered oil components (e.g., oxidized aromatics), which are not determined in the GC analyses. This conclusion is supported by Farrington *et al.* (1986), who suggest that non-agreement between UV/F and GC results is due to the presence of fluorescing hydrocarbons other than the aromatics normally determined by GC methods.

Any immediate changes in animal oil content caused by the surface oil release in Bay 11 are masked by the effects of the dispersed oil release in Bay 9. Only small increases in oil concentrations of Bay 11 organisms were measured in the first post-spill sampling (1981a; see Fig. 3a), which occurred before the dispersed oil spill in Bay 9. Gas chromatographic data for Bay 11 tissues (Table 7) do not indicate the presence of

petrogenic hydrocarbons except for biota from one sampling station (Engelhardt and Norstrom, 1982). However, by the second post-spill sampling period (two weeks after the dispersed oil spill in Bay 9), oil content of Bay 11 organisms was similar to that of organisms from all other bays for the same period. Results of later samplings, in particular those from 1983, indicate that oil is entering the benthic system two years after the experimental releases. While this material has the UV/F characteristics of the experimental oil, gas chromatography data do not indicate the presence of the lower molecular weight hydrocarbons that were present in 1981.

Filter feeders residing in Bay 7 exhibit the greatest increases in oil concentration after the dispersed oil release. This is not expected from the level of exposure to dispersed oil experienced by these animals (see Table 5). The sea floor of Bay 9, the site of the dispersed oil release, was exposed to concentrations of oil well above 50 $mg \cdot l^{-1}$ for more than 12 h, with an integrated exposure of 300 $mg \cdot l^{-1} \cdot h$ (Humphrey *et al.*, 1987). Bay 10 benthos were exposed to maximum concentrations and integrated exposures of $\frac{1}{10}$ the levels of Bay 9, while Bay 7 animals were exposed to levels one order of magnitude lower again. Body burdens, as determined by UV/F, vary inversely to the hydrocarbon content of the water to which the animals were exposed. *S. groenlandicus* is the most obvious example. The data in Table 5 compare the hydrocarbon exposure levels (Humphrey *et al.*, 1987) to the first post-spill body burdens. While the differences in body burdens are not as extreme as the differences in exposure, they decrease with increased exposure. The difference in uptake may be related to some behavioural defense mechanism in Bay 9 and 10 animals in that they may have stopped pumping water for the period of intense exposure, while those in Bay 7 were not sufficiently stressed to invoke a similar reaction.

Results from later samplings do indicate differences in hydrocarbon uptake between different feeding types. The deposit feeders *M. calcarea* and *S. droebachiensis* increase their oil contents after 1982. Results of the sediment analyses in the experimental area show that sediment oil content is also increasing (Boehm, 1987). The oil concentrations of Bay 11 and 9 sediments have increased from less than 1 $mg \cdot kg^{-1}$ in both bays in 1980 and 1981 to 13 $mg \cdot kg^{-1}$ in Bay 11 and 8 $mg \cdot kg^{-1}$ in Bay 9 in 1983. This source of hydrocarbon is available to the deposit feeding animals. An anomaly is the filter feeder *M. truncata*. For no apparent reason, the hydrocarbon content increased for *M. truncata* samples in all three of the sampled bays in 1983.

Gas chromatographic compositional analyses also show some general patterns. Most animals took up fresh oil immediately after the dispersed oil release, followed by loss of both aliphatic and aromatic hydrocarbons, as indicated by decreases in overall body burdens of these components. *In vivo* degradation of the *n*-alkane components of the oil was also indicated by the presence of a more biodegraded aliphatic fraction in the tissue samples than was present in either the water column or sediments at the same sampling period. There did not appear to be general differences in the composition of hydrocarbons taken up by filter and deposit feeders, although differences in depuration rates (Fig. 3) and characteristics (Tables 7-10) between species were evident. In other BIOS experiments, Mageau *et al.* (1987) conducted tank simulations using this same oil and dispersant and also observed *in vivo* oil biodegradation in *M. truncata* and *S. groenlandicus* specimens.

The GC/FID data (Tables 7-10) suggest that *A. borealis* degrades aliphatic components of oil very rapidly, although both UV/F and GC/MS results indicate that the aromatic components do not degrade at a rate different from that in other animals. A greatly accelerated *in vivo* degradation is confirmed for *A. borealis* vs. other bivalves in that initial oil residues (1981a sampling) from Bay 7 *A. borealis* tissues contained no *n*-alkane components lighter than C_{20}, while Bay 7 *M. truncata* and *S. groenlandicus* contained substantial *n*-alkane character in the C_{14}-C_{20} region (Boehm, 1982). The extent of this biodegradation is greater in Bay 7 animals than in Bay 9 and 10 animals sampled at the same time, but this may be related to the higher overall levels of acquired petroleum in the Bay 9 and 10 organisms.

S. droebachiensis also provides some interesting detail. The GC/FID analyses indicate that little oil is taken up by the urchins, yet the UV/F and the GC/MS indicate significant uptake. Mageau *et al.* (1987) also noted the near absence of petrogenic components in the F1 aliphatic fraction of *S. droebachiensis* extracts but observed only low concentrations of some petrogenic aromatics in the F2 fractions. It is possible that urchins degrade or depurate the aliphatic components so rapidly that they are not readily observed.

Most animals appear to retain aromatic components of the oil longer than aliphatic components. These observations are consistent with the results of Roesijadi *et al.* (1978) and are consistent with known patterns of biodegradation in which aliphatic components are most easily degraded by bacterial action.

The appearance of some low molecular weight aliphatics and aromatics in the 1982 tissue samples suggest that there may be a source of relatively fresh oil near the experimental sites. This effect was observed in all bays and may have been a consequence of oil leaching off the beach in Bay 11. Much of this stranded oil remained unweathered, probably due to its small surface area to volume ratio. The levels of fresh oil in the tissues were very low in all cases and were not observed again in 1983.

These results indicate that all biota accumulated petrogenic hydrocarbons following the 1981 experimental spills. The dispersed oil spill caused an immediate but short-lived infusion of oil to the water column and resulted in temporary accumulation of hydrocarbons by the benthos. These conclusions were also reached by Mageau *et al.* (1987) based on tank simulations of the BIOS dispersed oil spill. Similar patterns of oil accumulation and release by the various organisms studied were also observed in the field spill and in the tank simulations. Hydrocarbon levels in all species had returned to near baseline levels by 1983 except in Bay 11 (surface oil release), where oil concentrations were still slightly elevated. It is possible that oil stranded on the Bay 11 beach was still providing a source of petrogenic hydrocarbons to Bay 11.

A comparison may be made of the results of this work to those of a similar experiment carried out at Searsport, Maine (Page *et al.*, 1983; Gilfillan *et al.*, 1985). Although no exposure estimates were made for their untreated oil experiment, an estimate of the bottom exposure during the treated oil experiment (10% Corexit 9527 in Murban oil) was similar to the exposure observed in Bay 10 of the BIOS experiment. A significant difference between the experiments was that their method of spilling the oil mimicked a real spill situation more closely than did our procedure. The oil/dispersant mixture was spilled on the water surface and dispersed into the water column using breaker boards; a consequence was that very little lower molecular weight material reached the bottom.

Chemical monitoring of samples of *M. arenaria* and *M. edulis* from well before the discharge until the following year showed that no treated oil was assimilated by these species. Significant uptake of oil by these species from the untreated oil was observed, with depuration to pre-discharge levels within three to six weeks. In both species, the uptake of aromatic material was relatively higher than the oil composition would predict, and the uptake and depuration in *M. arenaria* was faster than in *M. edulis*.

Although direct comparison of the results of the two experiments is not possible, certain similarities are apparent. Both experiments indicate that although rapid uptake of hydrocarbons was observed, depuration to near background levels also occurred in a short time. The apparent preference for aromatic hydrocarbons was also observed in both experiments. Neither experiment was able to distinguish between the possible mechanisms of this preference; preferential uptake of aromatic hydrocarbons and preferential degradation or depuration of aliphatic hydrocarbons will generate the observations. These observations are consistent with those of Rice *et al.* (1984) that aromatics accumulate in tissues more readily than do aliphatic hydrocarbons.

The arctic location of the present experiment may have a significant effect on the results. Owens *et al.* (1987) show that the fate of stranded oil on the beach in this experiment can be related to temperate situations by considering the open water periods only. This means that the input to the subtidal regime in the Arctic may continue for a much longer period than would occur in temperate climates, providing a continued source of potentially toxic hydrocarbons to the benthic communities at the time of greatest growth. This chronic stress may be more harmful than an acute stress in temperate waters.

CONCLUSIONS

Dispersed oil reached the benthic community and was rapidly taken up by the biota. Filter feeders absorbed oil more rapidly than deposit feeders, but both types did accumulate oil. Some animals appeared to have a defense mechanism in the presence of high concentrations of hydrocarbon and did not accumulate as much oil as those exposed to lower concentrations. *In vivo* degradation occurred, with apparently different rates in different species. The biota affected by the dispersed oil degraded or depurated most of the oil within one year.

The surface untreated oil did not reach the benthic community immediately and was not taken up by the biota. The oil stranded on the beach provided a long-term low-level chronic input to the biota.

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