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THE PHYSICAL PERSISTENCE OF SPILLED OIL: AN ANALYSIS OF OIL SPILLS PREVIOUS TO EXXON VALDEZ

FINAL REPORT

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1.0 INTRODUCTION

The purpose of this report is to provide a comprehensive literature review focusing on the actions and environmental recovery of past spills in light of the EXXON VALDEZ spill in Alaska. Spills selected for review were based on similarity of climate, shoreline types, and biological populations. Special emphasis was placed on studies resulting from the 1978 AMOCO CADIZ spill of Brittany, France, and the 1974 METULA spill in the Strait of Magellan. Both spills matched the selection criteria and were of comparable magnitude to the EXXON VALDEZ spill. The experimental oiling program undertaken in Baffin Island, Canada, also provides excellent comparisons to the Alaskan oil spill.

During the review process attention was concentrated on the relative effectiveness of the cleanup methods used, the role of natural processes in oil removal, and the persistence of oil within the affected environment one to three years after the incident. In several cases, long-term studies enable our knowledge of spill persistence to be extended far greater than three years after the event. These studies corroborate previous observations and, therefore, are also discussed.

1.1 REVIEW PROCESS

The oil spills reviewed in this report serve as possible analogues to the EXXON VALDEZ spill. A list of the spills reviewed and their general features is included in Table 1.1. The data from the analyzed spills vary in quality. Several major oil spills, e.g., the IXTOC I and BURMAH AGATE, both affecting the sand beaches of Texas, are not included here because impacts on sand beaches are better discussed under the AMOCO CADIZ spill. Finally, it must be emphasized that there has never been a spill of this magnitude in Alaskan environments nor with Prudhoe Bay crude oil, so specific rates of asphalt formation, microbial degradation, chemical attachment to sediments, and biological recovery in Alaska are unknown.

Table 1.1. Principal oil spills evaluated in this report.

Spill/Date	Location/Climate	Oil/Amount
ARROW/February 1970	Chedabucto Bay, NS/Northern Maritime	Bunker C/10,090 tons
METULA/August 1974	Strait of Magellan, Chile/Northern Semi-arid	Arabian Light Crude/51,500 tons
AMOCO CADIZ/March 1978	Brittany, France/Northern Maritime	Arabian/Iranian Light Crude 225,000 tons
BIOS Experiment/1980-1982	Baffin Island, NWT/Ice-dominated, Northern	Lago Medio Crude/variable

2.0 ARROW OIL SPILL, NOVA SCOTIA (1970)

2.1 INTRODUCTION

After grounding on rocks in Chedabucto Bay, Nova Scotia, on 4 February 1970, the tanker ARROW lost approximately 10,090 tons of Bunker C oil [Ministry of Transport (MOT), 1970]. While Bunker C oil is not directly comparable to Prudhoe Bay crude oil, it is of value to briefly review the long-term persistence of oil at this locality as illustrative of the potential for spill longevity within the sheltered environments of Alaska.

2.2 CLIMATE AND COASTAL CONDITIONS

The spill site is located in a triangular embayment between mainland Nova Scotia and Cape Breton Island. The south coast of the bay is developed along a fault line inducing a relatively steep shoreline. In contrast, the north coast has relatively low-lying topography. A variety of shore types are present, including rock outcrops, eroding till cliffs, gravel, and mixed sediment beaches. The area is climatically dominated by its maritime setting, producing cold, wet winters and cool summers.

2.3 IMPACT AND CLEANUP

During the spill, some 240 to 300 km of shoreline were oiled (Owens, 1971; Vandermeulen and Gordon, 1976; Keizer et al., 1978), although the quantity of oil onshore was not determined. A variety of shoreline types were affected including sand and gravel beaches and exposed rocky shores. The focus of this report is on the sheltered mixed sand and gravel beaches where oil remained longest and which are most comparable to Alaska.

Two and a half months after cleanup, MOT (1970) estimated that 1,800 tons, or 18% of the original amount, remained. Vandermeulen (1977) prepared a series of maps illustrating oil persistence along the shore from the initial event to six years later (Figure 2.1).

Cleanup of the area included effective manual pickup of oily debris, and less effective mechanical removal of sediments (primarily gravel) which mixed oiled material deeper into the beach, contaminated clean backshore environments, caused additional damage while gaining access to the shore, and induced erosion of the backshore (Owens, 1971; Owens and Rashid, 1976). In some cases, clean sediment was brought in to replace removed oiled gravel. Scrapers were partially effective on compact sand beaches and of little value on coarser gravel beaches.

2.4 PERSISTENCE STUDIES

Long-term studies of the ARROW spill noted that oil remained as asphalt pavement within the sheltered environments whereas areas exposed to wave action were reworked and cleaned (Owens, 1971; Owens and Rashid, 1976). In the low-energy area of Black Duck Cove, the latter authors report the "... physical abrasion of the oil has been negligible and the

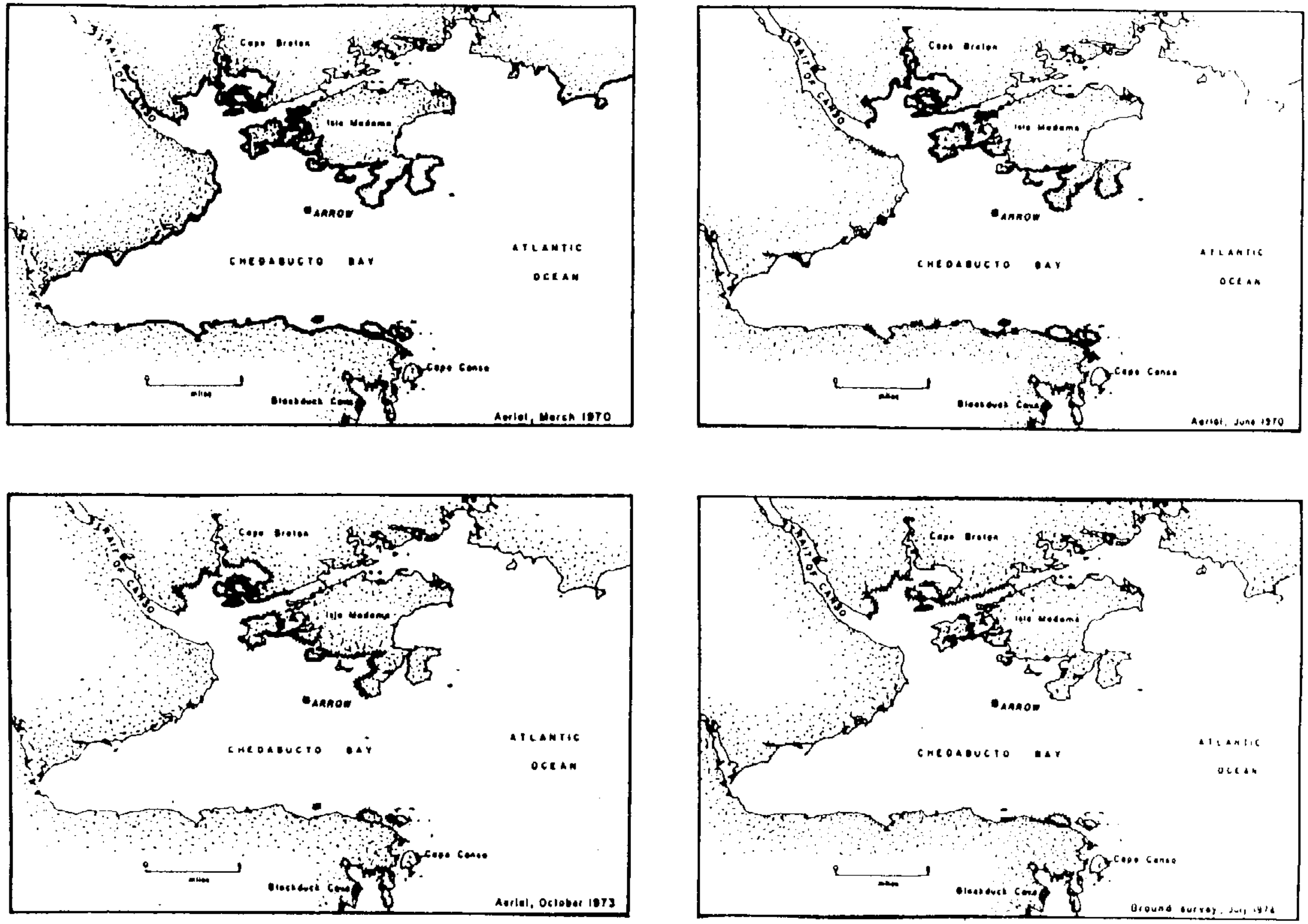

Figure 2.1. Distribution of Bunker C residues along the shores of Chedabucto Bay resulting from the ARROW spill of 4 February 1970 (from Vandermeulen, 1977).

extent of oil cover has not changed significantly since 1970." They also report that chemical evidence indicates that the rate of chemical/biological degradation of the remaining oil is very low. Vandermeulen and Gordon (1976), using florescence spectroscopy, estimate that the leaching of oil from the stranded Bunker C is on the order of parts per billion. After nearly eight years of physical and chemical weathering, Vandermeulen (1977) still found "considerable amounts of the fuel oil in some isolated areas, and traces in others." Vandermeulen (1977) summarized self-cleaning and biological recovery in the diagram presented in Figure 2.2, which indicates a three-year removal rate of oil from all high-energy beaches, and longer than seven years as sheltering increases.

2.5 BIOLOGICAL IMPACT AND RECOVERY

Studies of the ecological impact of the ARROW spill cover a time span from immediately post-spill to 1977. Impacts were reported from the intertidal zone on rocky shores and sand beaches and from coastal marshes.

Thomas (1975) stressed that all of the early biological studies of the ARROW spill impact suffered from a narrow focus. Too few species were included in the initial surveys. A second problem, which is the usual case for most oil impacted areas, was the complete lack of pre-spill ecological surveys. Thomas suggested that the only acceptable analysis of the data would be completely dependent on obvious changes from the normal for the whole area.

2.5.1 Rocky Shores

Two species of fucoid algae showed disparate responses to ARROW oil. Populations of Fucus spiralis, a high intertidal rock-encrusting algal species, were heavily damaged by oiling. They quickly disappeared from the heavily oiled shoreline and were still absent in 1975. A second fucoid, F. vesiculosis, occupies the lower intertidal on Chedabucto Bay rocky shores. Following the ARROW incident its intertidal range decreased in height. Through 1975 its range gradually increased back to normal. Throughout this period fucoid sporelings recruited to the upper intertidal but they never survived to the point at which they could be identified.

Barnacles (Balanus balanoides) appeared to suffer no unusual mortalities following oiling. Barnacle larval settlement and growth seemed normal from 1970 to 1975. Three algal grazing gastropods, Littorina saxatilis, L. littorea, and L. obtusata, remained abundant in the intertidal in heavily oiled areas. The vertical range of L. obtusata contracted due to the loss of algal habitat in the upper intertidal.

A more extensive survey of the biota began at six years post-spill (Thomas, 1978). The overall design was based on the selection of four oiled and four unoiled control sites. Species abundances or biomasses were determined at each site, based on replicate samples, and were compared for differences in these attributes by nested ANOVAs. The

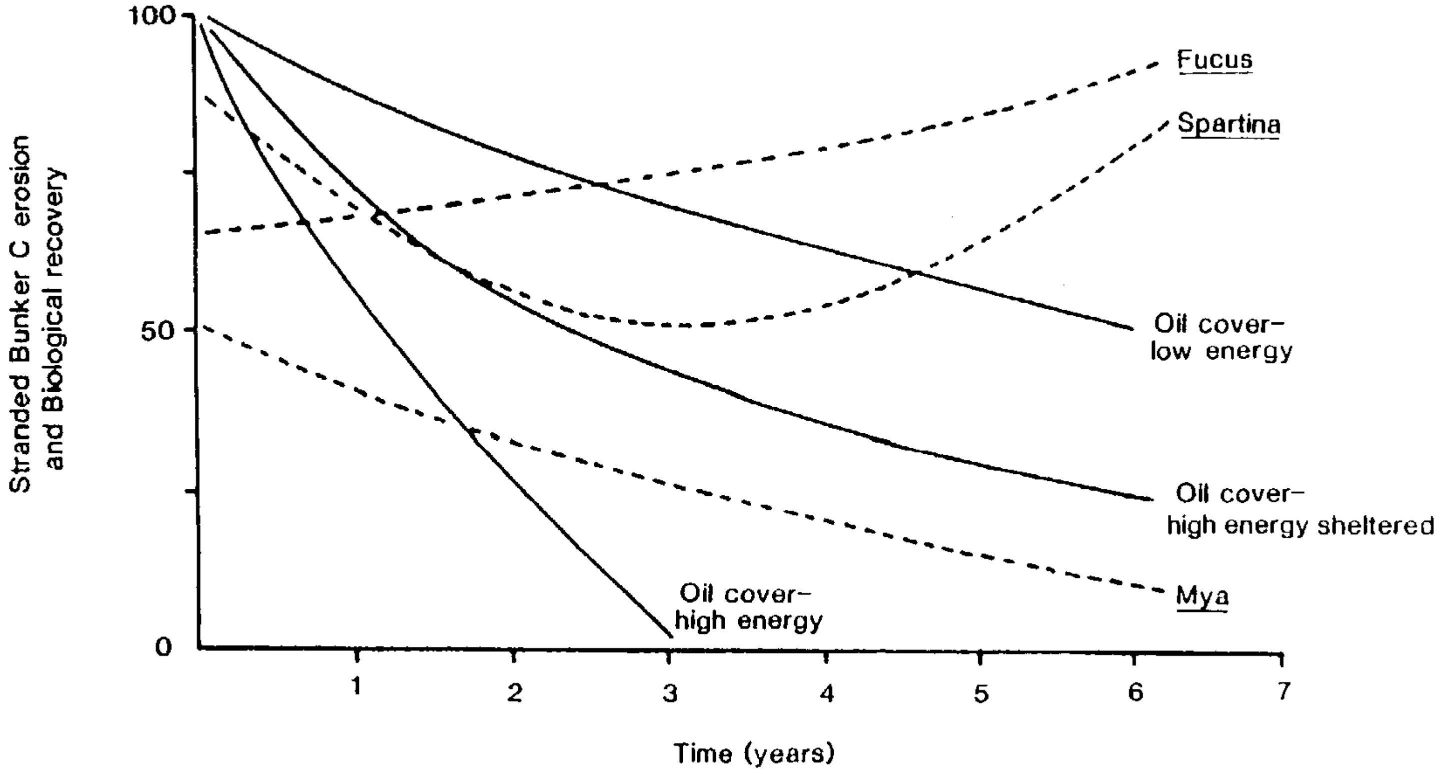

Figure 2.2. Summary of self-cleaning and biological recovery processes (from Vandermeulen, 1977).

rocky shore control sites had a greater number of species than did rocky oiled sites. Six of the 10 most common species were more abundant at control sites. The most obvious large difference between oiled and control sites was that the total biomass of flora at control sites was 3.14 times that measured at oiled sites.

Analyses of length and weight for Littorina littorea and Mya arenaria data were also presented in Thomas (1978). Regressions of length on weight of these species separated out across oiled and control sites while population densities of these species were not different between treatments. The growth rates of both species were slowed by oil and not by increased population densities.

Numerous other comparisons of oiled and unoiled sites produced significant differences in this excellent study. A well-planned, post-spill study can produce very useful information even in the complete absence of pre-spill surveys. Thomas also looked at the effect of cleanup techniques and concluded that recovery rates were decreased by the cleanup procedures used on rocky shores.

2.5.2 Sedimentary Shores

The most conspicuous species in sheltered Chedabucto Bay soft sediment communities was the clam Mya arenaria. Much of the oil spilled by the ARROW was locked up in ice during the first post-spill winter. Clam mortalities increased as this oil was released when the ice cover melted (Thomas, 1975). The mortality rate has declined since the first post-spill spring. Initially clams left their burrows as the burrows filled with oil; exposed clams were eaten or died for other reasons.

At six years after the spill (Vandermeulen, 1977) clams were greatly reduced in abundances, their age distributions were altered, and a six-year-old size class was missing from heavily oiled populations. Vandermeulen concluded that clams in chronically oiled sediments were under a great deal of stress. Stranded oil was slowly being released into the littoral and sublittoral environment in heavily oiled areas. Most of the stranded oil moved through the sediments and in interstitial waters; very little of the oil was detectable in the water column. The water column concentrations detected after five years were not sufficient to inhibit photosynthesis or to kill crustacean larvae. Much of the sediment was immobilized by stranded oil. The effects of this immobilization on the benthos was not known.

Thomas' (1978) extensive post-spill survey included sedimentary shores. He concluded that since oil was more persistent on such shores cleanup might be helpful if the oil could be removed by techniques which did not increase sediment penetration. Some evidence of a natural biogenically-mediated weathering process was provided by Gordon et al. (1978). The polychaete Arenicola marina (a burrowing deposit feeder found in sandy areas of Chedabucto Bay) assisted in removing oil by increasing microbiological degradation rates of oil in its castings. A density of 10 to 25 worms/m^2 could remove all oil from a 1 m^2 area in 2 to 4 yr. Their overall conclusion was that oil-tolerant deposit-feeding animals can accelerate weathering of sediment-bound oil.

2.6 SUMMARY

The ARROW spill is important since it was the first North American spill to receive adequate scientific and technical attention to document cleanup effectiveness of various shorelines and to determine that the long-term persistence of oil was related to shore type and exposure. The scientific literature indicate that within Chedabucto Bay's sheltered environments, Bunker C from the ARROW remained relatively unchanged for at least eight years. Recent reports by Owens (visual presentation, 1988) and others indicates that asphalt from the spill is still evident today, although in a very degraded state.

The biological impact of the oil spill, expressed as declines in biomasses and densities of many common species of benthic biota, was still stongly evident six years after the spill.

2.7 INCLUDED REPRINTS

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Owens, E.H., and M.A. Rashid. 1976. Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia. Can. Jour. Earth Sci., vol. 13, pp. 908-928.

Thomas, M. L. H. 1978. Comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia. J. Fish. Res. Board Can. 35:707-716.

Vandermeulen, J.H. 1977. The Chedabucto Bay Spill, Arrow 1970. Oceanus, vol. 20(4), pp. 32-39.

3.0 METULA OIL SPILL, CHILE (1974)

3.1 INTRODUCTION

The supertanker METULA (206,000 dwt) ran aground in the Strait of Magellan, Chile, on 9 August 1974. Over the next 1.5 months approximately 51,500 tons of light Arabian crude oil and 2000 tons of Bunker C oil were released into the Strait affecting 65 to 80 km of shoreline (Figure 3.1). Because no cleanup was performed, the spill site serves as a natural laboratory to monitor the long-term persistence of oil within a high-latitude environment.

Principal references for the METULA spill are Gunnerson and Peter (1976) and Hann and Young (1979) on initial shoreline impacts, Baker et al. (1976) and Straughan (1978) on short-term biological impacts, and Colewell et al. (1978) on microbiological changes. Followup studies were undertaken by the Instituto de la Patagonia, located in adjacent Punta Arenas, Chile, concerning the effects of the METULA on macrobenthos (Langley and Lembeye, 1977), vegetation (Pisano, 1976; Dollenz, 1977, 1978) and insects (Lanfranco, 1979). Guzman and Campodonico (1980) summarized these Chilean studies.

Evaluations of the persistence of oil in the Patagonian shorelines, most related to this analysis, have been completed by Hayes and Gundlach (1975) for oil remaining one year later, Blount (1978) on the persistence and oil quantification one to two years later, Gundlach et al. (1982) for persistence 6.5 yr later, and Owens (1987) on persistence and chemistry of the oil after 12.5 yr.

3.2 CLIMATE AND COASTAL CONDITIONS

The climate of the Strait of Magellan is classified as modified steppe. Temperatures are similar to the Alaska spill site with a monthly mean of 14°C in summer and close to 1°C in winter, with much variance about the mean. Ice cover is infrequent and precipitation is very low (less than 30 cm per yr). The area is quite arid supporting only sparse grasses and few trees.

The principal coastal environments of the METULA spill site are mixed sand and gravel beaches, and mud/sand-dominated tidal flats. Like many parts of the EXXON VALDEZ spill site, the beaches of Patagonia were deposited by glacial action. Many similarities such as exposure, climate, and sediment type exist between these beaches in Chile and those of Alaska. At the METULA site, there are also extensive tidal flats and a few areas containing salt-tolerant vegetation (comparable to a marsh).

The tides of Patagonia are roughly similar to those of Alaska, varying from greater than 6 m outside the First Narrows to 3 to 6 m in the embayment adjacent to the grounding site. Fetch and wave conditions are similar to areas in Alaska with low to moderate exposure, specifically those within Prince William Sound and in the fjord embayments of the Kenai Peninsula.

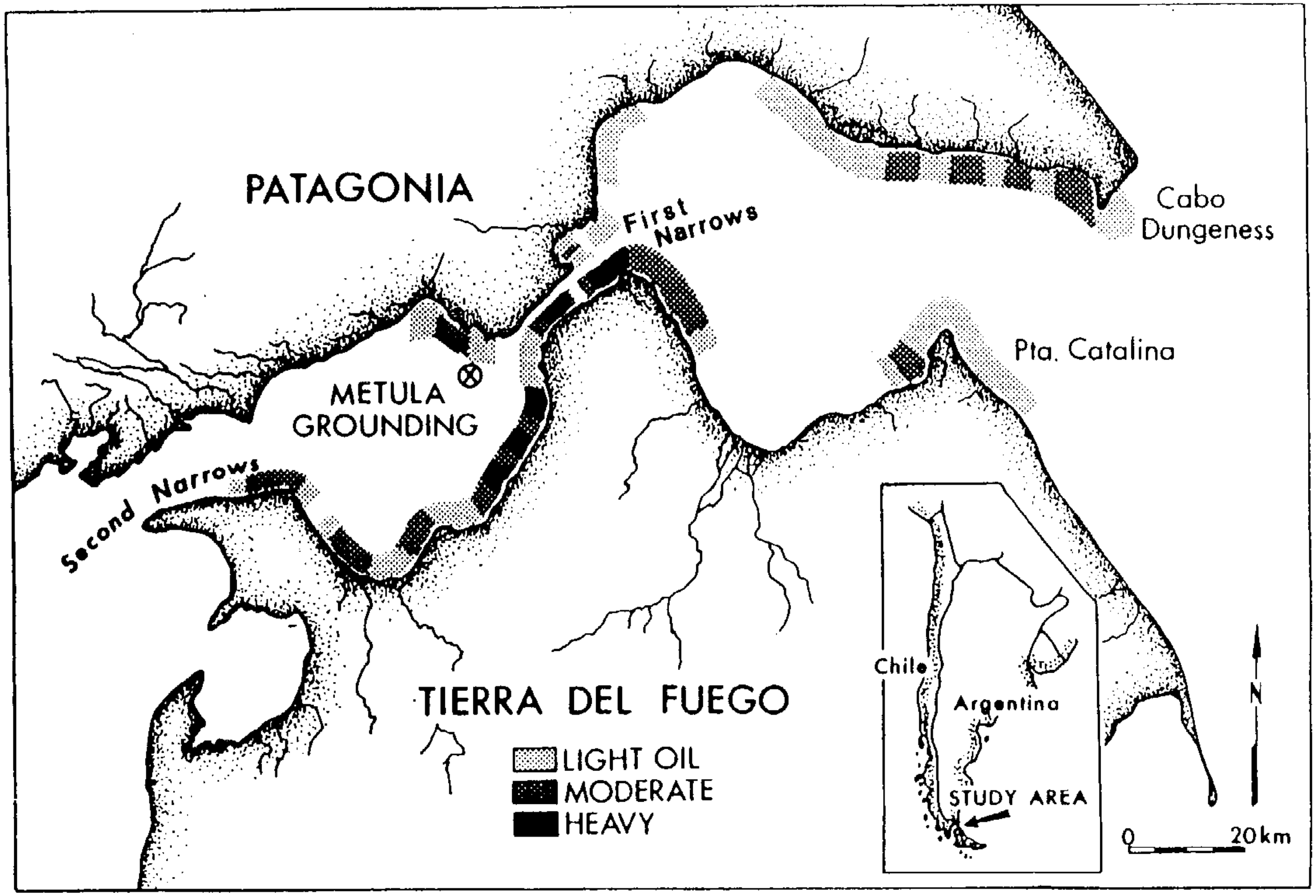


Figure 3.1. Location site and oiling resulting from the METULA spill of 9 August 1974.

3.3 INITIAL IMPACT AND CLEANUP

Oil from the METULA was rapidly spread by wind and tidal currents, forming thick mousse accumulations against the shoreline. Coverage of the intertidal zone ranged from almost total to very patchy. Mixed sand and gravel beaches composed over 95% of the affected shoreline, but marshes and tidal flats were also affected, particularly in the region of the First Narrows.

Marshes, in particular, are not common in Patagonia. Unfortunately, an area dominated by salt-tolerant vegetation (designated Espora marsh) located in the First Narrows near Punta Espora was heavily oiled. Since no cleanup was undertaken, the Espora marsh serves as a "type locality" to illustrate the effects of heavy oil accumulations on a high latitude marsh system. Oil thicknesses averaged several centimeters over the marsh surface. Primary vegetation consisted of _Salicornia_ _ambiqua_ (saltwort) and _Suaeda_ _argentinenis_ (sea blite).

No cleanup was undertaken except for the area of a small boat ramp to the ferry that crosses the Strait. While never explicitly stated, probable reasons that no cleanup was undertaken include: a) the government was concerned with other matters, having recently overthrown the elected government of Salvador Allende, b) the ship was directed by a Chilean pilot at the time so expenditures against the international oil pollution fund would likely have to be reimbursed by Chile, and c) cleanup had no political support due to the remoteness and low population of the area.

3.4 PERSISTENCE STUDIES

3.4.1 Mixed Sand and Gravel Beaches

On mixed sediment beaches in Patagonia, which are most comparable to Alaska, Hayes and Gundlach (1975) described two primary sites of oil deposits remaining after one year: along the spring high tide swash line and the upper part of the low-tide terrace. An aerial photograph of these oiled zones in Chile is presented in Figure 3.2 (top), and compared to oil along Elizabeth Island in Alaska (Figure 3.2, bottom). A diagram indicating oil distribution after one year is presented in Figure 3.3.

The formation of asphalt pavement was particularly ubiquitous in Chile (Blount, 1978). Not only was it found along the upper low-tide terrace, but also on the beach face in cases where mousse had originally mixed and solidified into the gravel. Deposits of asphalt reached almost 20 cm thick, and showed relatively fresh oil in its interior, away from external weathering processes. To determine the oil concentration within sediments, Blount (1978) analyzed numerous samples and found tremendous variation in values, ranging from near zero to over 30% by volume (Figure 3.4). Followup studies by Gundlach et al. (1982) 6.5 yr after, and by Owens et al. (1987) 12.5 yr post-spill tracked the oil along these beaches. Oil remained obvious even after 12.5 yr of weathering and some reworking of the sediments by waves.

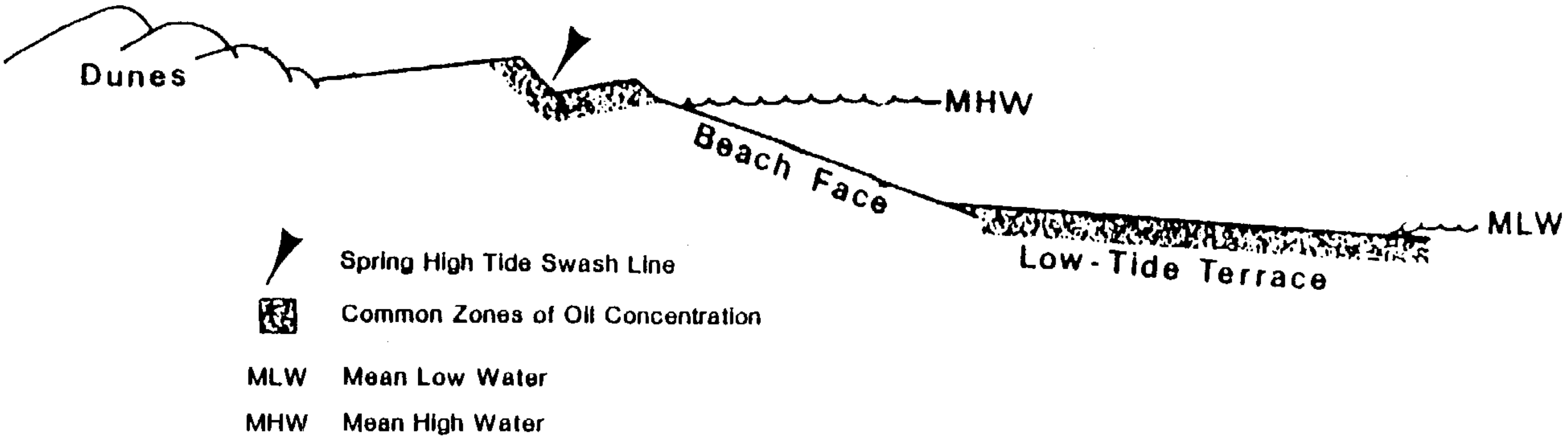


Figure 3.3. Diagram indicating zones of METULA oil remaining 1 yr after the incident on moderately exposed mixed sand and gravel beaches (*Modified from:* Hayes and Gundlach, 1975).

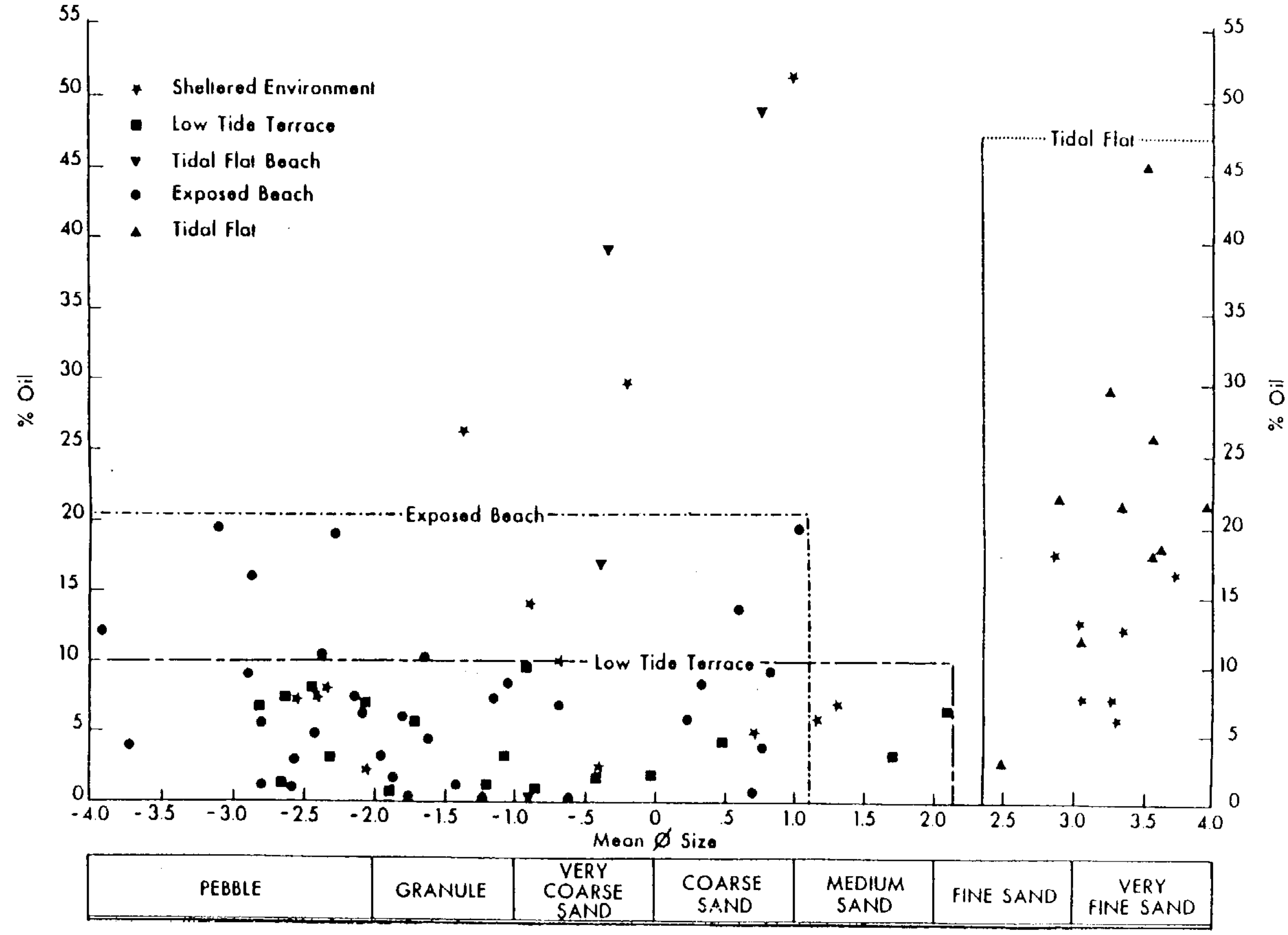


Figure 3.4. Chemical analyses of METULA sediments 1.5 yr after the incident (from Blount, 1976).

Remaining oil can be divided into two types. The first type includes oil deposited along the upper berm, above the zone of reworking by spring tides (see photograph in Figure 3.5, top). After 6.5 yr, oil was most commonly found as crumbly, asphaltized sediment buried beneath a surface of gravelly sand (Figure 3.5, bottom). During the interval since the spill, wave action had not sufficiently reworked the sediments to break up the remaining oil. After 6.5 yr, however, the material was highly weathered and could be easily broken apart with one's fingers and did not stain nor yield a sheen.

The second and more common type of remaining oil was asphalt pavement, particularly within the area of the First Narrows (see photograph in Figure 3.6, top). Generally, this pavement was thicker than pavement observed in Alaska over the summer of 1989 (see Figure 3.6, bottom), although further asphalt formation may occur in Alaska. The thick asphalt pavements in Chile still showed some brown mousse in its interior after 6.5 yr, and was described by Owens et al. (1987) as "fresh, almost fluid and apparently unweathered" after 12.5 yr. An analysis of that sample, reported by the same authors supported that it was relatively fresh, although microbial degradation was occurring. Owens also found that asphalt remained common in sheltered areas. Sites more exposed to wave action showed a loss of all low-tide terrace pavement within 6.5 yr, and most beach face pavement (as along the First Narrows) within 12.5 yr.

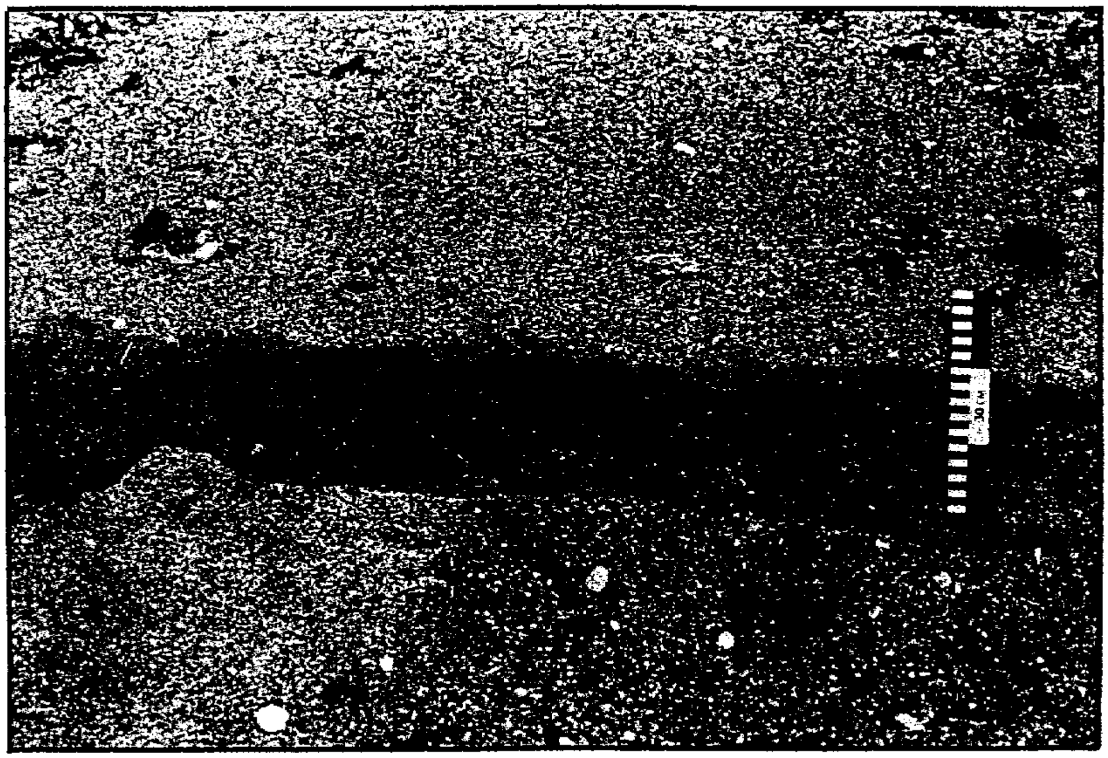
3.4.2 Tidal Flats

The Chilean spill site contained one set of tidal flats that was open and exposed, and another that was very sheltered. On the exposed flat, oil was pushed over the flat up to the high-tide swash line, although the amount of oil so transported was very small. After 6.5 yr, a small amount of weathered oil, similar to a dried tar in appearance, was present along the upper flat (Gundlach et al., 1982).

The persistence of oil was considerably more obvious in sheltered tidal flats, as along the First Narrows. A thick asphalt pavement persisted over 12.5 yr, with little change, on a major flat behind a protecting spit. An adjacent flat showed a thinner pavement, but also little degradation.

3.5 BIOLOGICAL IMPACT AND RECOVERY

As previously monitored, the METULA spill was unique in that virtually no cleanup attempts were undertaken. Various aspects of the spill's biological impact were studied by Dollenz (1978), Langley and Lembeye (1977), Lanfranco (1979), Pisano (1976), Colwell et al. (1978), and Guzman and Campodonico (unpublished manuscript). The most comprehensive spill-effects study (Straughn, 1978) was started at five months post-spill (January 1975) and repeated at basically the same set of sites two years later (January 1977). Straughn used a study design which allowed statistical comparisons between oiled and unoiled control sites. She selected a variety of statistical methods to analyze the census and oil content data collected at each of the study sites.


30 cm

3.5.1 Rocky Intertidal

In January 1975, large areas of the intertidal zone were still covered by METULA oil (Straughan, 1981). In at least one heavily oiled, upper intertidal site, oil bound sandy sediments into a solid asphaltic bed. The lower intertidal was rocky and it was richer in species in both oiled and control sites than was the sandy upper intertidal zone.

Fewer organisms, larger numbers of empty mussel shells in good condition, and other evidence of the previously more extensive mussel beds differentiated oiled sites from control sites. Since there were no pre-spill data, the evidence was not conclusive to unequivocally demonstrate that the noticeable differences between control and oiled sites were a result of oiling. However, mortalities of mussels were recent, oil had been present in large amounts for five months, and the differences between oiled and control sites correlated more closely to the presence of oil than to measurable differences in physical factors.

At five months a thick layer of mousse deposited in the lower intertidal had not dried out. Straughan (1981) speculated that recolonization of the lower shore should proceed as the mousse dried out to form a hard asphaltic substratum or as the mousse degraded. The presence of a black layer of asphalt was predicted to have a strong effect on zonation patterns due to the heat retaining properties of the asphalt.

Two years later (January 1977) several complications affected Straughan's ability to interpret the data. Sea temperature had increased by 2°C throughout the area and oil from other sources was present on some of the original survey sites. The increased sea temperature apparently produced an overall biotic change in the area. Despite these complications two important conclusions were drawn. It was evident that little faunistic recovery had occurred at the heavily oiled quadrats at Site I despite the removal of some petroleum. Faunistic recovery had begun at all other oiled sites but it was still hampered by the presence of petroleum.

3.5.2 Saltmarshes

Vegetation in saltmarshes was initially damaged but seemed to be recovering rapidly as evidenced at five months post-spill by shoots which pushed up through the oil. The evidence in 1977 showed that saltmarsh plants at Site I were not doing well; there was a continuing "decrease of flora" at this site (Straughan, 1981). Five and a half years later, very little overall recovery of marsh vegetation was observed (Gundlach et al., 1982). In the heavily oiled area (18 hectares in size), almost all vegetation was dead. Only Salicornia showed some 10 to 30 cm of lateral new growth directly over the oiled surface. Roots of the plants, however, did not extend into the oil. The same condition was noted at the AMOCO CADIZ spill site after the incident. In addition to 18 hectares of heavy oiling, 23 hectares of Suaeda vegetation were killed as the oil floated in on a high spring tide, oiling only the vegetation and not the substrate. The killed vegetation did not recover; however, the area supported new vegetation when observed 6.5 yr after the spill. Twelve years after the incident, Owens et al. (1987) observed a 1 to 2 cm "latex" layer over the marsh surface. Photographs of the marsh one year after compared to 6.5 yr after the spill show little change (Figure 3.7).

3.6 SUMMARY

The METULA site provides a good analogue to the Alaska situation. Climates are generally similar; both are relatively cool, although the eastern Strait of Magellan receives much less rainfall. In Chile, asphalt pavement, created where mousse mixed into coarse sediments, took more than 6.5 yr to degrade, even in some moderately exposed locations. In sheltered areas, the asphalt pavement persisted greater than 12.5 yr. In sheltered areas, e.g. Espora Marsh, where an asphalt pavement did not form, oil also degraded extremely slowly. Along the upper portion of the beaches, (similar to where EXXON VALDEZ oil is most commonly found), degraded oil persisted longer than 6.5 yr in zones where wave action was not sufficient to rework the sediments.

Evidence of a very slow recovery of coastal biological communities was provided through a well-designed sampling procedure. Saltmarsh damages were immediately noticed, but some recovery of some saltmarsh plants was evident at five months. These plants did not fare well. This situation should be compared to the AMOCO CADIZ spill (Section 4.0); several saltmarshes were extensively oiled and massive cleanup operations worsened the damage. In both cases recovery was very slow.

3.7 INCLUDED REPRINTS

Gundlach, E.R., D. Domeracki, and L.C. Thebeau. 1982. Persistence of METULA oil in the Strait of Magellan, six and one-half years after the incident. J. Oil and Petrochemical Pollution, Vol. 1(1), pp. 37-48.

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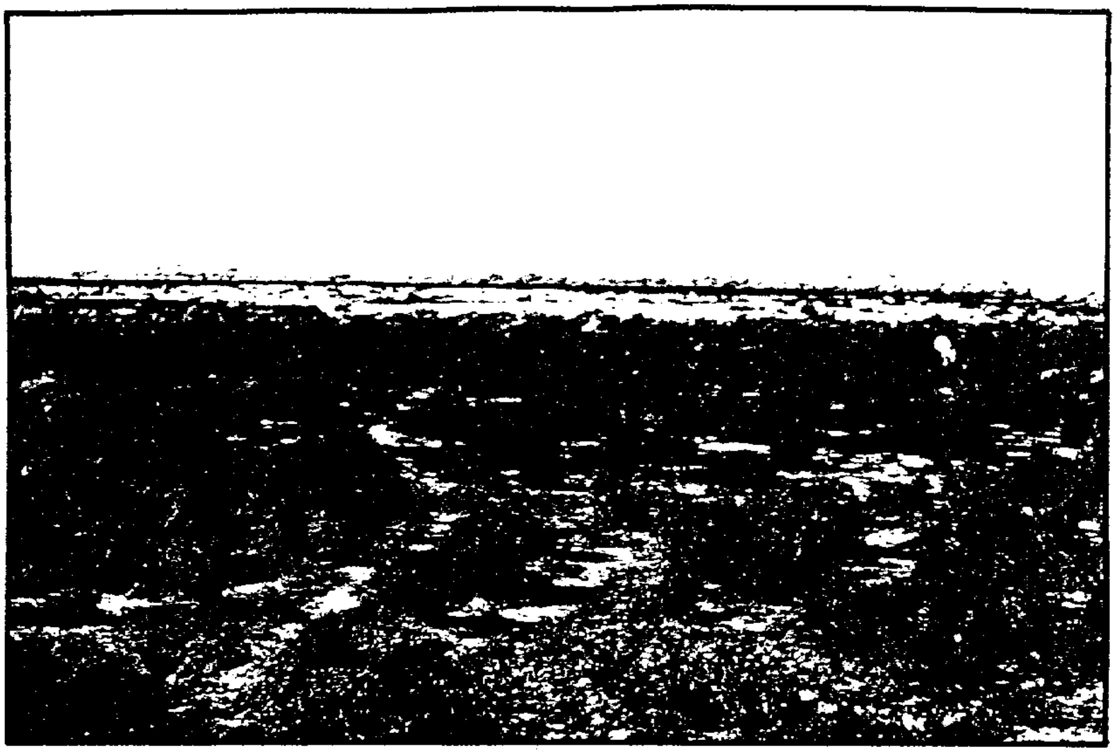


4.0 AMOCO CADIZ, BRITTANY, FRANCE (1978)

4.1 INTRODUCTION

The AMOCO CADIZ oil spill was the largest spill ever to affect coastal waters. Altogether, 223,000 metric tons of light Arabian and light Iranian crude oil, plus some 2000 tons of Bunker C oil were spilled off the coast of Brittany after the ship grounded on 16 March 1978. After initial hesitation, France mobilized a large-scale cleanup using the military as well as local hires. Because of excellent coastal access, most oiled areas were treated in one form or another.

The French spill remains as one of the most studied spills in history. The spill occurred in the immediate vicinity of the French governmental oceanographic institute (CNEXO, now called IFREMER) and the oldest marine laboratory (Roscoff) in Europe. In addition, joint projects were undertaken with scientists from the United States under initial support of NOAA and later by the Joint Franco-American Commission funded by Amoco. Numerous other scientists from many other nations also completed studies of the spill and its effects.

Principal references on the spill, which primarily contain summary proceedings or reports, are Hess (1978) on the initial impacts, Conan et al. (1978) and Spooner (1978) on effects during the first three to six months, NOAA/CNEXO (1982) on summary reports after three years, and Gundlach et al. (1983) presenting a single article on initial and longer-term (three years) impacts. Other reports on the distribution of oil are provided by CNEXO/IFP/IGN (1978), Berne and D'Ozouville (1979), and D'Ozouville et al. (1981). Hann et al. (1978) provide a summary of the cleanup in terms of manpower and methods by which the oiled material was processed. Additional material on the spill and its effects was produced during the AMOCO CADIZ trial in Chicago (1987-1988). Specific documents produced during litigation are not included in this report; however, observations are presented which were made during French or Amoco sponsored field surveys undertaken in 1983-1986.

4.2 CLIMATE AND COASTAL CONDITIONS

The climate of Brittany is temperate, strongly influenced by the Gulf Stream. In comparison to the United States, it is more climatically similar to the West Coast near Oregon or Washington than to the U.S. East Coast. It has cool and wet winters and summers. Snow is unusual.

The maritime climate of Brittany is dominated by storms generated in the North Atlantic which track from west to east and periodically cause very high winds and seas along the coast. Waves over 6 m are common during these events. During the spill in March and April 1978, at least two storms of this magnitude hit the coast. Like Alaska, not all of Brittany is exposed to such wave conditions. Many parts of the coast are entirely sheltered and showed the longest persistence of oil. Tides in Brittany are 6 to 9 m, comparable to Alaska's.

Coastal Brittany is composed of bedrock headlands with high wave exposure, broad sand beaches similar to those of the Alaska Peninsula area, mud-dominated estuaries (not found in the Valdez spill area), seagrass meadows (Zostera marina)--also found in Alaska (Hood and Zimmerman, 1986), long stretches of mixed sand and gravel and cobble beaches, and scattered marshes. Many sites serve as possible EXXON VALDEZ analogues.

4.3 INITIAL IMPACT AND CLEANUP

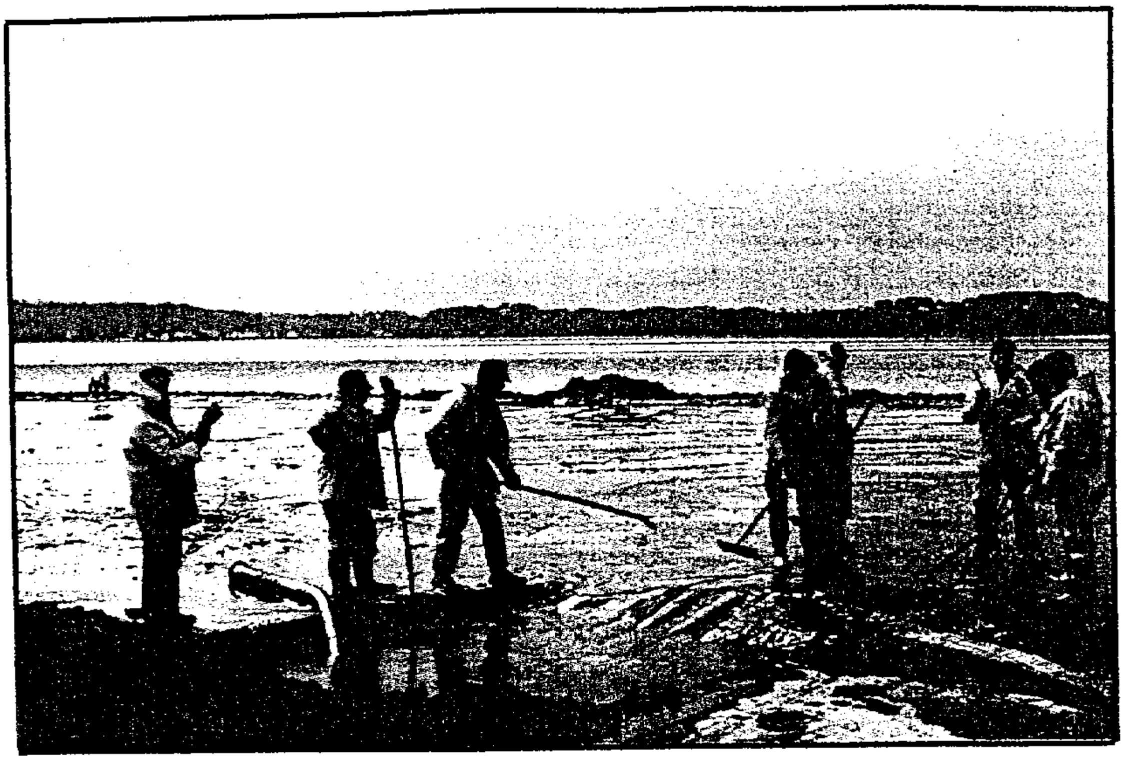
Similar to Alaska, AMOCO CADIZ oil first concentrated in thick pools within few embayments and beaches affecting a limited amount of shoreline during the initial stages of the spill. Heavy oil pools (e.g., see photograph in Figure 4.1, top) were specifically mapped as covering 72 km of shoreline during the first two weeks of the spill. In both France and Alaska, the pools of oil dispersed before being collected, spreading the oil in lesser concentrations over a much greater area. In France, the total extent of oiling increased to 320 km one month after the spill; however, the amount of oil onshore dropped from approximately 64,000 tons onshore to less than 15,000 tons.

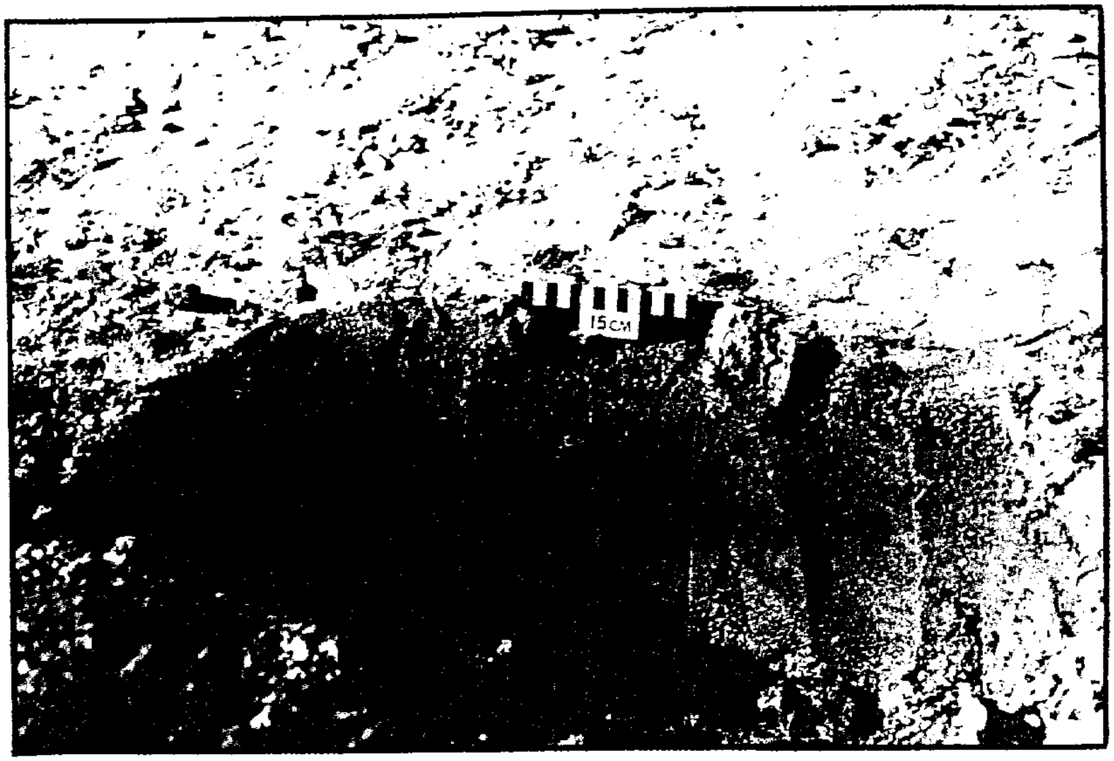
The mobilization of cleanup equipment and manpower at the AMOCO CADIZ spill site was slow. Large booms placed to protect the estuaries and the sensitive resource areas (e.g. a lobster hatchery and marine laboratory) were ineffective due to strong currents and the enormous quantity of oil.

The next phase of response utilized "honey wagons" or small tanks towed by tractors to collect the oil. The honey wagons and some tank trucks collected oil directly from the water surface or from collection pits dug into the beach (Figure 4.1, bottom). Skimmers were rarely used. In some cases, oiled sand was removed by front-end loader.

The third phase of cleanup utilized high-pressure flushing and physical manipulation of the shoreline after oil concentrations dissipated. The flushing activity used fire-hoses and, in selected instances, a perforated hose producing a constant flow. The manipulation of the shoreline included the moving of oiled gravel and cobbles into the surf zone, or lower onto the beach (the low-tide terrace) with the intention that they would be more exposed to wave action and natural cleansing (see photograph in Figure 4.2, top). In areas where sediments normally had high mobility, and where oily material was not placed below the active beach face, the sediments were successfully cleaned with no change in beach characteristics. However, in cases where material was placed on the low-tide terrace below the active beach face, sediment did not return to the beach face.

Oiled material collected from the shore was housed in temporary, land-based storage pits and then transported to two centralized dump sites. The material was all treated with quick-lime for encapsulation and stabilization. The site was later covered over and is now part of the dock facilities in Brest and recreational tennis courts in Tregastel.

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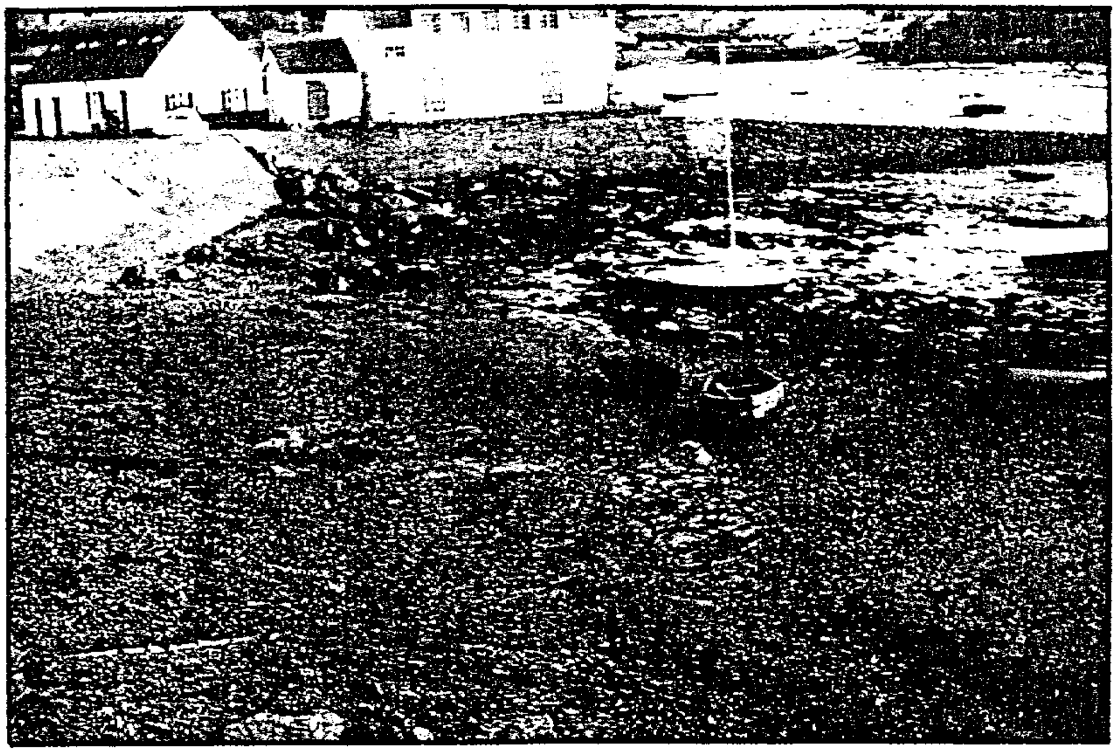

The final stage of cleanup used hot-water, high-pressure wands to remove the oil stain from the rocks and seawalls, particularly in areas of high-recreational use (see photograph in Figure 4.2, bottom).

After treatment, minimal shoreline restoration occurred. The oiled marsh at Ile Grande received the most attention and large areas were replanted after the almost total destruction of the lower marsh. At other sites where oily material was stored on land in pits, or where access was created through a dune field, the site was cleaned up and replanted. No restoration of the collection pits occurred so that oil could still be found there at least eight years later (see photographs in Figure 4.3). Remnant scars from the use of heavy equipment on the shoreline, similarly, were not treated (see photograph in Figure 4.4, top; and comparison from EXXON VALDEZ, Figure 4.4, bottom). Finally,. there was no attempt made to restore areas where gravel was moved lower on the beach face but had not returned. Claims against Amoco for erosion as well as for aesthetic impacts were successfully made by the local French governments long after the cleanup teams had departed.

4.4 PERSISTENCE STUDIES

Studies of persistence at the AMOCO CADIZ site were complicated by the Tanio oil spill of March 1980 (also discussed herein) which impacted much of the same Brittany coast. After a hiatus from roughly 1981 to 1983, additional studies began when Dr. Fichaut of Brittany, under contract to the French litigation team, walked much of the previously impacted shoreline. Additional followup studies were undertaken by Fichaut, Gundlach, and others in 1985 and 1986. Results of the study on marsh recovery have been published (Baca et al., 1989).

4.4.1 Sand Shorelines

Impact of the sand beaches of Brittany was followed for several years after the spill. Along fine-sand areas, oil was removed naturally by wave action in a fairly rapid manner. In some cases, oil was manually collected from the beach because of easy access and the ability of the substrate to support heavy vehicles. On coarser sand beaches, normally steeper and subject to deeper oil burial, oil persisted in many areas as subsurface oil layers for at least nine months after the spill until storm waves reworked the beach. At a very limited number of beaches that were not naturally reworked, it appears that AMOCO CADIZ oil may have persisted for at least eight years as degraded oil within the beach.

4.4.2 Rocky Shores

Along rocky shores exposed to moderate to high wave action, oil persistence was generally very short, on the order of weeks, at the AMOCO CADIZ site. However, in a limited number of exposed areas that contain small microhabitats sheltered from direct wave action, such as behind boulders or in sheltered clefts in the rock, oil persisted as an asphalt crust for several years. Along rocky shores within quiescent embayments, asphalt crust formed where oil settled between the rocks and was not treated during cleanup.

4.4.3 Mixed Sand and/or Gravel Shorelines

These shorelines varying up to cobble-sized were extensively treated by high-pressure flushing and/or physical manipulation. In boulder-dominated areas, either the surface was spray-cleaned with hot water or the site was left to recover naturally. In areas where either cleanup or natural wave action removed the majority of the oil, oil stain and tar could be found on the rocks for at least two years, and longer in certain sites. Liquid or free oil was not evident. In areas that oil was left to remain on the shore without treatment and away from physical reworking, asphalt crust formed. As supported by the ARROW and METULA studies, this crust is likely to be found along certain shores in Brittany today.

4.4.4 Tidal Flats

The large tidal range in Brittany exposed numerous flats of mud, sand and sandy gravel, to AMOCO CADIZ oil. Some of the flats near Roscoff are covered by the seagrass Z. marina (denHartog and Jacobs, 1980). Mud-dominated flats showed the longest persistence of oil (probably continuing until today), but are uncommon in the EXXON VALDEZ spill site. Sandy and sandy gravel flats are most common in Brittany. In these areas where cleanup was undertaken (using heavy equipment and open pits to collect the oil), surface contamination was reduced but oil was also mixed deeper into the sediments. Oil remained present within the sediments as liquid oil for more than two years at many locations (Gundlach et al., 1983). Followup studies by Fichaut (unpublished) indicated that the liquid oil remaining in tidal flats was fairly extensive throughout the spill site, although by 1985 and 1986, it had been reduced to isolated pockets, primarily located in areas where cleanup trenches or pits were used. On the coarser-grained flats composed of sandy gravel, asphalt pavement persisted for at least eight years where oil settled into the sediments. Photographs of an oil degradation sequence within Portsall Harbor are included in Figure 4.5.

4.4.5 Marshes

As indicated by Baca et al. (1989), several types of marshes were impacted by AMOCO CADIZ oil. The marsh at Ile Grande was most affected, first by the oiling which was several centimeters thick over the entire surface, and then by the cleanup which utilized heavy equipment and excessive hand-labor. After eight years, nearly full recovery of marsh vegetation was observed, although remnants of both the oil and cleanup were visible. In two other localities, the oiled marsh surface (but not the underlying fine-grained substrate) was removed and had grown back again. In sites where oiling was generally lighter, oiling only the surface of the vegetation, the marsh recovered after several years, although thicker concentrations within the marsh vegetation asphaltized. In marshes where mousse patties stranded between the grasses along the marsh fringe, the patties turned to an asphalt crust over time, but did not disappear.

4.5 BIOLOGICAL IMPACT AND RECOVERY

Biological impacts of the AMOCO CADIZ oil spill are described in studies of habitats similar to those found in Prince William Sound (Hood and Zimmerman, 1986). Tidal flats, rocky headlands, gravel and rock strewn beaches, muddy and sand beaches in sheltered bays, and saltmarshes were oiled by the AMOCO CADIZ spill. The immediate biological impacts of the spill on these habitats were reported by Cross et al. (1978), Hyland (1978), Chasse (1978), and Dauvin (1982). Longer term ecological studies which began soon after the spill and extended for periods of up to 12 yr include Gundlach et al. (1981), Vandermeulen (1981), Dauvin (1982), Baca and Lankford (1987), Gorbault (1987), and Bodin (1988). Brief descriptions of the reported effects of the spill on each of these habitat types are provided in Table 4.1.

4.5.1 Tidal Flats and Beaches

Tidal flats in the area affected by AMOCO CADIZ oil suffered varying degrees of biological impact which seemed to be primarily dependent on wave energy (Gundlach, 1981). Oil had little impact on exposed low-tide terraces where it rapidly flowed over the compact sand surfaces. In a more depositional environment (St. Michel-en-Greve), oil killed much of the infaunal community. This impact was partially due to the presence of dispersed oil in the water column. The severity of the ecological impact at other sites (at three months post-spill) was related to the amount of oil (Table 4.2).

Studies of the effects of oil on Zostera marina meadows are of interest here because they describe the effects of oiling on several ecological guilds. Two long-term studies of the seagrass-covered tidal flats began in October 1977 (six months prior to the AMOCO CADIZ spill). Oil reached the Roscoff grassbeds on 20 March 1978. A study of the benthic infauna (Jacobs, 1980), which lasted until April 1979, indicated that various faunal groups responded differently due to their feeding habits and location in or above the sediment surface. Polychaetes living below the sediment surface within the thick mat of seagrass roots and rhizomes were not strongly affected because oil could not mix with the root-bound sediments. Their populations recovered rapidly. Filter feeding infauna and those species which inhabit the sediment surface were most strongly affected. Echinoderms and small crustaceans almost completely disappeared but populations of many species, with the exception of amphipod species, recovered within one year. Only short-term effects on the seagrass plants could be detected. This study is important because it describes the most comprehensive post-spill research on the effects of AMOCO CADIZ oil on intertidal and just subtidal ecological communities.

A second study of tidal flat communities, the epifauna of seagrass beds (den Hartog and Jacobs, 1980), deals with the animals which live above the sediment surface. This fraction of the total seagrass community is less likely to be similar to tidal flat communities in Prince William Sound. However the epifaunal study does support the infaunal study in that filter feeders were most strongly affected and had not completely recovered after one year.

Table 4.1. References to relevant biological impacts of the AMOCO CADIZ spill at varying intervals after the 16 March 1978 spill off the coast of North Brittany.

Reference	Studies Habitat	Dates	Observations
Chasse (1978)	Rocky shores	1978	Restricted use of dispersant, rough sea conditions, and immediate collection of oil reduced damage levels...general cover of macroalgae survived the incident; barnacles, mussels, and reef-building sabellariids low in the intertidal initially were not affected. Herbivorous gastropods and certain crabs were strongly affected. A shrimp became very abundant apparently due to increases in its prey, a meiofaunal copepod.
	Mud and sand		Polychaetes were remarkably resistant; Lamellibranchs, mostly quite seriously depleted; various levels of mortality among amphipods and echinoderms (heart urchins and brittle stars were nearly all killed while a burrowing holothurian had good survival).
	Mobile fauna		Certain crabs and shrimp were strongly affected; emaciated and diseased fish were common in the oiled area.
Jacobs (1980)	Seagrass infauna	Oct 1977- Apr 1979	Small Crustacea and Echinodermata almost disappeared; other infauna also less numerous; recovery for most groups was rapid, filter-feeding Amphipoda recovered slowly. Seagrass beds formed a protective shelter for many species.

Table 4.1. (Continued)

Reference	Studies Habitat	Dates	Observations
den Hartog and Jacobs (1980)	Seagrass epifauna	Oct 1977- Apr 1979	A very diverse assemblage of Amphipoda disappeared; replaced by two species. Some species recovered rapidly, but most filter-feeders did not.
Dauvin (1980)	Sublittoral	Aug 1977- Aug 1980	Population explosions of highly opportunistic species were documented; detritivorous polychaetes increased dramatically in abundance. This did not happen at a second, less chronically-polluted site.
Gundlach et al. (1981)	Rocky shores	May-Jun 1981	*Fucus* rapidly recolonized heavily oiled areas; areas dominated by *Ascophyllum nodosum* showed less recovery.
	Gravel beaches		No biological impact reported.
	Tidal flats		Postulated strong effect on infaunal community; the polychaete *Arenicola* common after the spill.
Vandermeulen et al. (1981)	Saltmarsh	1978-1980	Removal of surface sediments and deepening of drainage channels greatly increased erosion rates; effects could be countered by replanting vegetation or damming the marsh.
Seneca and Broome (1982)	Saltmarsh	1979-1981	Methods of marsh restoration tried at Ile Grande are described; success varied with species and transplantation method.

Table 4.1. (Continued)

Reference	Studies Habitat	Dates	Observations
Gourbault (1987)	Subtidal	1978-1984	Effects on nematode assemblages most noticeable at the shallowest upstream site; effects still detectable until four years after the spill. Difficult to detect effects at deeper sites against normal background variation.
Bodin (1988)	Beaches	1978-1984	Meiofaunal communities initially degenerated large decreases in density and diversity. Recovery began after the turning point year of 1981; the length of the recovery period was dependent on functional group memberships.
Baca et al. (1989)	Saltmarsh	1978-1986	Chronology of Ile Grande marsh work from 1978 through 1983; marsh recovery occurred within 4 to 5 years and may have been delayed by cleanup activities, a delay of 20-25%; recommends low-level cleanup and artificial planting; canal and dike construction should be avoided, if not avoided then damage should be repaired following cleanup; overall emphasis should be on protective measures.

Table 4.2. Summary of ecological effects 3 months after the AMOCO CADIZ spill on a heavily and on a lightly oiled locality.

	Percentage Survival	
Pollution Intensity	Portsall +++ +++	Plouguerneau ++
Algae on rocks	90	95
Barnacles	100	100
Herbivores (limpets and winkles)	8	65
Meiofauna on algae	>500	>300
Meiofauna in sand	12	17
Macrofauna in sand	40	80

Cross et al. (1978) reported strandings of millions of dead heart urchins (Echinocardium cordatum) and hundreds of thousands of razor clams (Ensis siliqua and Pharus legumen), cockles, small surf clams (Mactra cinerea), and worms on beaches near St. Efflam on April 12, 1977. Other less abundant species found dead on the beach included mussels (Mytilus edulis), small clams (Venerupis decussata, V. pullastra, Tellina tenuis, and Lutraria lutraria). A majority of the animals found stranded on the beach at St. Efflam were bivalves and most bivalves are filter feeders. A slight delay in the die-offs after the spill was attributed to one of two possibilities: either 1) massive amounts of oil were trapped by the coastline and water soluble hydrocarbon fractions from this oil took a few days to reach toxic levels or 2) dispersed oil (from dispersant use in offshore areas) reached the bay and accelerated the dissolution and altered the vertical distribution of the oil. The animals listed above were killed when oil reached the bottom. Most effects were due to oil alone since they were observed in areas where no detergents were found (Teal and Howarth, 1984).

By April 30 clean-up crews, waves, and tidal currents removed most evidence of these massive shallow-water die-offs from the beach. Live Tellina tenuis, which had been abundant in the intertidal zone at St. Efflam, also became difficult to find.

Chasse (cited in Conan, 1982) estimated that delayed mortality effects on sand and mud biota were substantial. At the St. Efflam beach, T. fabula began to disappear from the intertidal zone a few months after the spill. As of 1982 it was completely restricted to the subtidal. A second example of delayed effects was due to a reduction in fecundity of plaice (a bottom fish) in the Aber-Benoit. Records of plaice fecundity from previous years and control sites were used in this comparison.

Longer-term ecological changes have occurred in certain areas. Recruitment of bivalve species, including T. fabula has been highly variable from year to year since the spill. This lack of stability was attributed to an unstable age distribution in the parental populations. Certain oil-resistant or opportunistic species (Teal and Howarth, 1984) have replaced the normal benthic assemblages in several oil-affected areas. Capittelid and cirratulid polychaetes, Nephtys hombergi (a polychaete), and Ampelisca sarsii have replaced declining faunas in several oil-affected areas.

Impact reports based on a single or a few post-spill collection dates cannot provide an adequate picture of the consequences of a large spill. Long term, very gradual changes may produce lasting alterations in species composition.

4.5.2 Rocky Shorelines

The most exposed rocky shores (and their associated biota) of the Brittany coast were protected from oil by reflected waves. On sheltered rocky shorelines Fucus was initially killed by cleanup operations and by direct contact with oil in contaminated tidal pools. The most severe and lasting damage was to fucoid populations growing on rocky shorelines near the saltmarsh at Ile Grande. This marsh was heavily oiled and was subjected to massive cleanup operations. Despite these attempts at oil removal much oil remained in the marsh and continued to reoil rocky shore algal populations through August 1979. At Ile Grand, cleanup included the cutting away of oiled plants and the use of high pressure hoses with some infrequent use of detergents (Topinka and Tucker, 1981). Other heavily oiled fucoids underwent gradual mechanical weakening and were eventually lost. Some very heavily oiled fucoids were not lost. Ascophyllum was killed.

Despite continued re-oiling of the Ile Grande rocky shoreline, there were some initial signs of recovery by August 1979, in that all major fucoid species showed signs of being reproductively mature. Fucoid germlings were also found in the area. The presence of developing, mature, and spent reproductive tissues in adult plants and the presence of young plants was considered to be a very useful measure of recolonization potential.

Cross et al. (1978) reported a nearly complete die-off of limpets and periwinkles (both grazers of microalgae) immediately inshore of the wreck site. Oiled limpets in other areas survived by moving to unoiled rock surfaces. Mortalities of most animals occurred over a two-month period following the wreck. Some of the mortality on rocky shores was directly attributable to clean up activities. Steam and pressure-cleaned rocky shorelines at Meis-Vran lost their typical molluscan fauna. Limpets, in the low intertidal on these same rocks, survived beneath algae attached to the rocks.

Fauna living beneath boulders was greatly affected. Amphipods vanished and few isopods and crabs (Carcinus maenas) were left. Subtidal populations of ascidians, sponges, hydroids, crustaceans, and sea stars were in good shape.

4.5.3 Saltmarshes

The Ile Grande saltmarsh was very heavily oiled because it lay directly in the path of oil slicks which moved to the east along the north Brittany coastline. Slicks entered the marsh continuously during the first month after the wreck. Most of the marsh was covered by oil to depths of 5 to 20 cm and, in some areas, pools of oil reached depths of 50 cm (Vandermeulen et al., 1981).

Heavy machinery was used to remove the oil because it was considered futile to attempt to use other cleanup methods on this marsh. Much of the marsh vegetation and underlying sediments were removed. This changed the marsh profile, increased current velocities in some sections, and caused severe erosion of marsh sediments.

Seneca and Broome (1982) planted five species of marsh plants in an attempt to rehabilitate the severely damaged Ile Grande marsh. The success of their efforts varied with species and with elevations in the marsh. Baca et al. (1987) revisited this marsh in 1985 and 1986. Their data suggested that marshes had completely recovered in some areas and were on their way to recovery in other locations. Marshes which underwent the cleanup procedure described above recovered more slowly than those which were not cleaned at all. Significant revegetation through natural processes occurred after five years at a marsh which had not been cleaned. The site of the heavily oiled and cleaned marsh at Ile Grande was judged to be completely restored at seven to eight years after the spill. These differences were also at least partially attributable to differences in initial impacts. The impact of oil on marsh annuals and perennials and the sequence of recolonization by these plants varied from site to site.

4.6 SUMMARY

The AMOCO CADIZ provides a wealth of information concerning the effects of certain cleanup operations and the persistence of oil. During the first months of the spill (from April to June), the French cleanup was aggressive at removing the oil, frequently digging collection pits and physically manipulating the beaches. However, neither a followup treatment program to deal with problem areas and asphalt formation, nor a restoration program to return the beach to its normal condition was undertaken after the majority of the oil was removed. As a result, liquid oil remained in cleanup trenches and in isolated pockets, and asphalt crusts were fairly common, many years after the incident.

After three years, asphalt pavement usually 2 to 4 cm thick was the most visible remnant of the spill. Liquid oil within the sediments was much less common, and was primarily restricted to cleanup trenches, tidal flats, and fine-grained sediments. Remnants of AMOCO CADIZ oil were not commonly found along gravel berms or in the upper intertidal zone as occurred in Chile, perhaps reflective of the combined effects of the cleanup operation, high wave conditions, and the type of oil.

The AMOCO CADIZ enabled some simple degradation rates to be determined (Gundlach et al., 1982). **Figure 4.6** presents this information graphically showing the loss of oil within different environmental components. As indicated, the water column showed the most rapid loss of oil, occurring within three to four months. Subtidal sediments showed a gradual decline over a two-year period except in sheltered, mud-dominated areas (Abers) where losses were much slower. On the shoreline, the tonnage of oil dropped very rapidly within the first months, and then descended much more slowly. While the amount of oil dropped fairly rapidly, the actual distance along the shore which appeared oiled dropped much more slowly. **Figure 4.7** shows this decline presenting shoreline oiling for the first two years, divided into heavily oiled, and light-to-moderately oiled categories. The occurrence of the TANIO spill, discussed later, in March of 1980 prevented completing the curve beyond two years.

Biological impacts of the AMOCO CADIZ spill have varied between species, between habitat types, and among sites within specific habitat types. Cleanup operation aided recovery in some situations and delayed it in others. In the case of the Ile Grande saltmarsh, cleanup operations delayed marsh recovery and increased the frequency at which

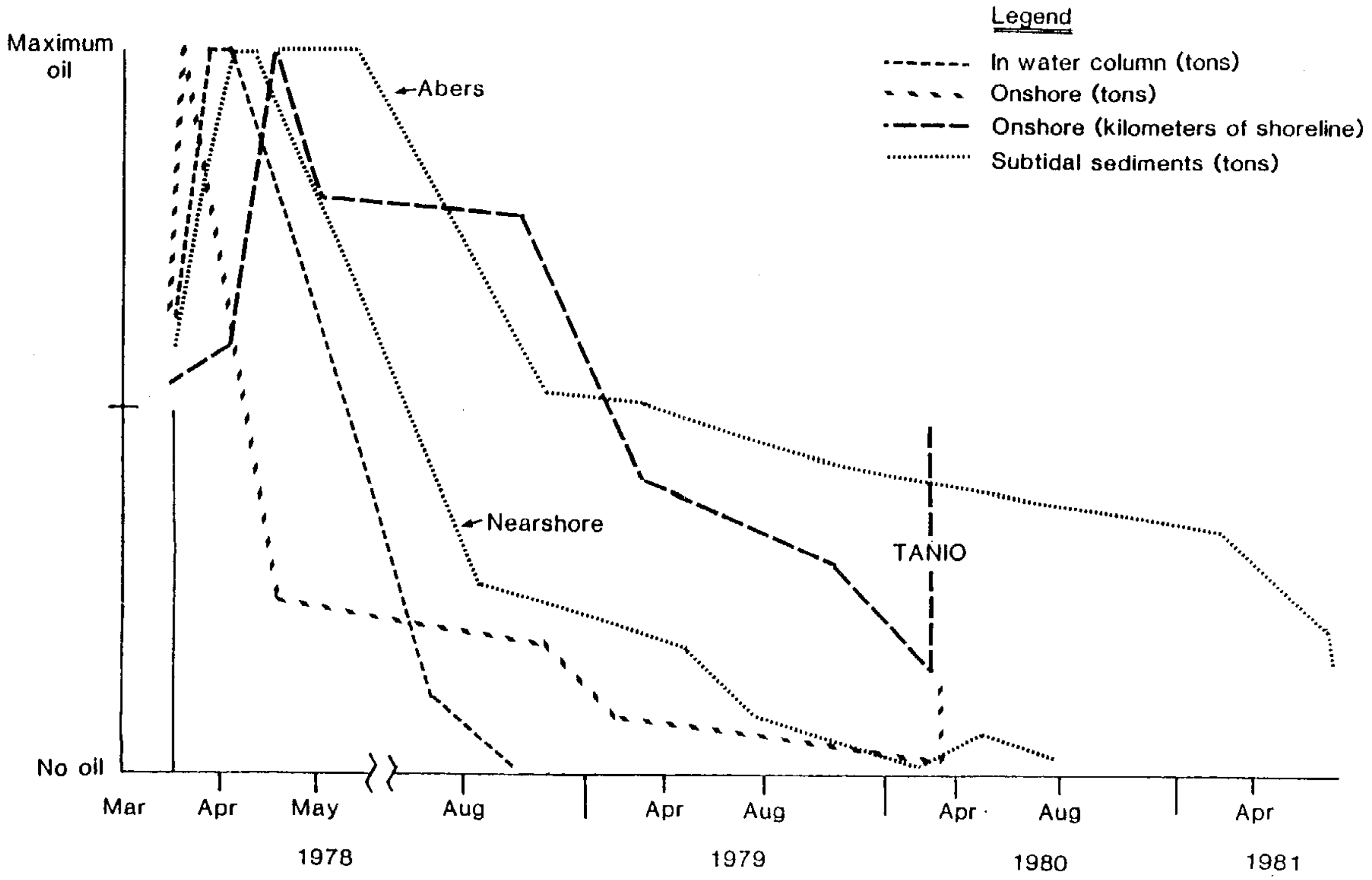

Figure 4.6. Synthesis of data relating to relative persistence of AMOCO CADIZ oil in the water column, subtidal sediments, and onshore, from March 1978 to April 1981 (from Gundlach et al., 1983).

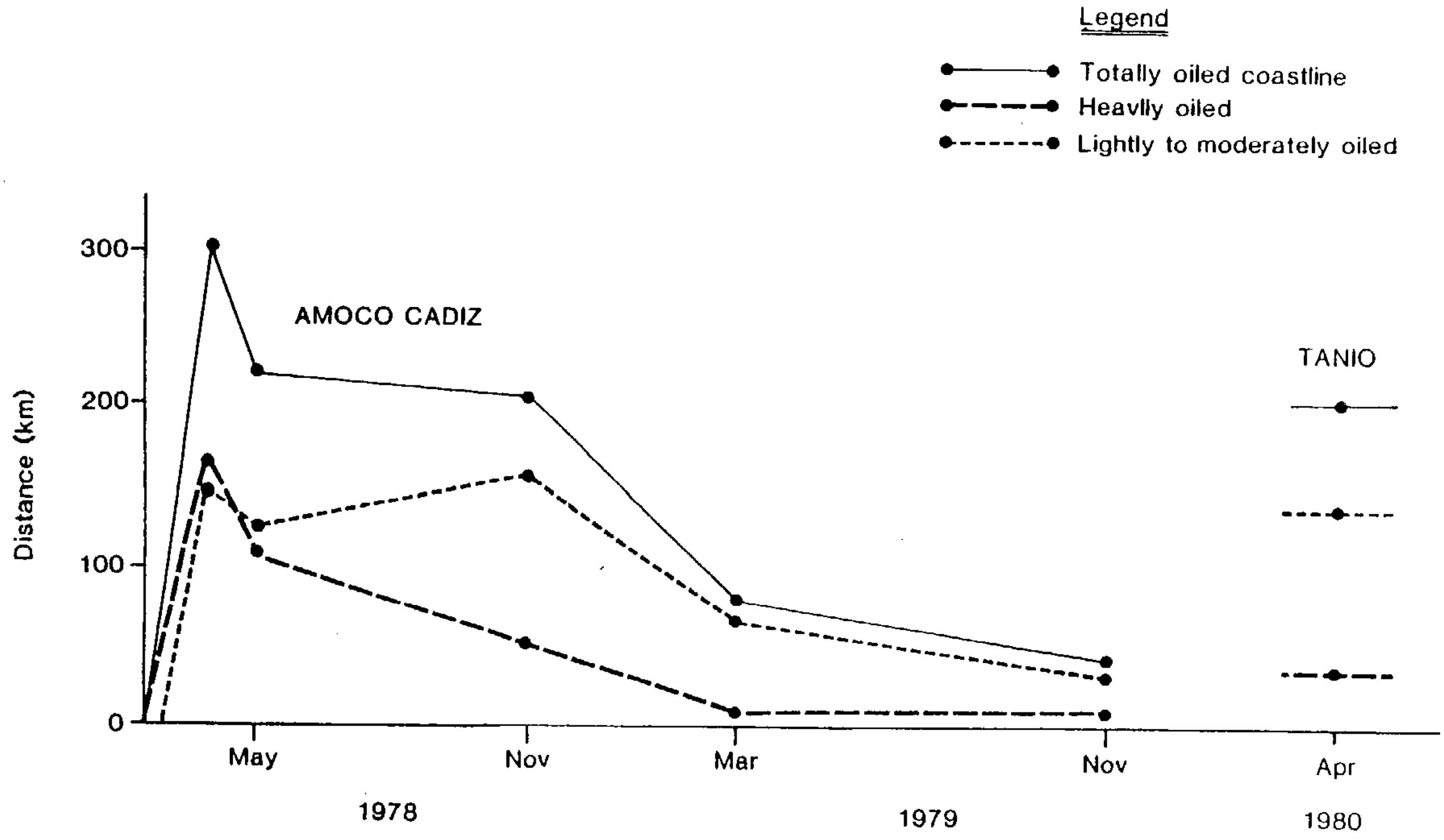

Figure 4.7. Extent of oiling from March 1978 to April 1980 (from Gundlach et al., 1983).

nearby rocky shores were reoiled. High pressure water and steam cleaning on rocky shorelines initially killed much of the rock crevice fauna but it is not known if the cleaning process aided long-term recovery by removing persistent oil.

A general problem with most post-spill studies is that most have been quite selective and limited in scope. It is very "likely that the presently known effects (of spills and of post-spill cleanup operations) are representative of a wider range that has occurred but which has not been detected" (Teal and Howarth, 1984).

4.7 INCLUDED REPRINTS

Gundlach, E.R., S. Berne, L. D'Ozouville, and J.A. Topinka. 1981. Shoreline oil two years after AMOCO CADIZ, new complications from TANIO. 1981 Oil Spill Conf., API Publ. No. 4334, Amer. Petrol. Inst., Wash. D.C. pp. 525-534.

Gundlach, E.R., P.D. Boehm, M. Marchand, R.M. Atlas, D.M. Ward, and Douglas A. Wolfe. 1983. The fate of AMOCO CADIZ oil. Science, vol. 221, pp. 122-129.

5.0 BIOS EXPERIMENT SITE, BAFFIN ISLAND, CANADA (1980-1982)

5.1 INTRODUCTION

The Canadian-sponsored BIOS (Baffin Island Oil Spill) experimental oiling site on Cape Hatt, North West Territories, offers some very appropriate analogues to the Alaskan spill site. The BIOS site was chemically and visually evaluated over many years providing a basis for long-term comparisons to the EXXON VALDEZ oil spill. Although limited analysis of the BIOS study sites is continuing, this report focuses on the first three to five years after oil was placed down. A summary volume concerning the program was prepared by Sergy (1987). The primary material relative to oil persistence was obtained from Owens et al. (1984), Owens et al. (1987), and Owens et al. (1990, pre-publication).

5.2 SITE CONDITIONS

The experiments at the Baffin Island spill site consisted of a series of exposed and sheltered intertidal as well as backshore sites where emulsion and crude oils were artificially applied in 1980, 1981, and 1982. A map showing the spill location is presented in Figure 5.1.

Sediment types at the BIOS site are mixed sand and gravel, comparable to many Alaskan shorelines, particularly depositional areas (e.g., spits, glacial beaches, and some sheltered areas). There is little to no comparison between the site and the exposed, very coarse (boulder, cobble) beaches of Alaska.

Exposure to wave action varies, but is generally moderate to low, similar to Prince William Sound and other areas within embayments. It is not comparable to the high-energy conditions of the open Gulf of Alaska or Shelikof Strait regions. The climate is colder and more ice dominated. The open-water season is approximately three months.

5.3 EXPERIMENTAL AND CONTROL PLOTS

5.3.1 Above Intertidal Zone Oiling (Control Plots, 1980)

Oil placed above the intertidal zone in 1980 (Bay 102 H1, H2) showed relatively little visual removal from 1983 to 1985. The plots continued to have a dark, weathered-oil surface, with black, oiled sediment beneath the surface. However, chemical data taken throughout the time period indicate a substantial reduction had taken place during the first three years after placement. The plot in Figure 5.2 of oil remaining based on Owens et al. (1984, Table 2.2) illustrates this trend. The reason for the reduction is not analyzed, but was considered as possibly due to leaching.

5.3.2 Low-energy Intertidal Oiling (1980)

While the study of land oiling (above the intertidal zone) has only limited extrapolation to the EXXON VALDEZ, the evaluation of low-energy, intertidal oiled plots is especially relevant. The BIOS study utilized two small plots in 1980 (Bay 103 L1, L2), one with aged

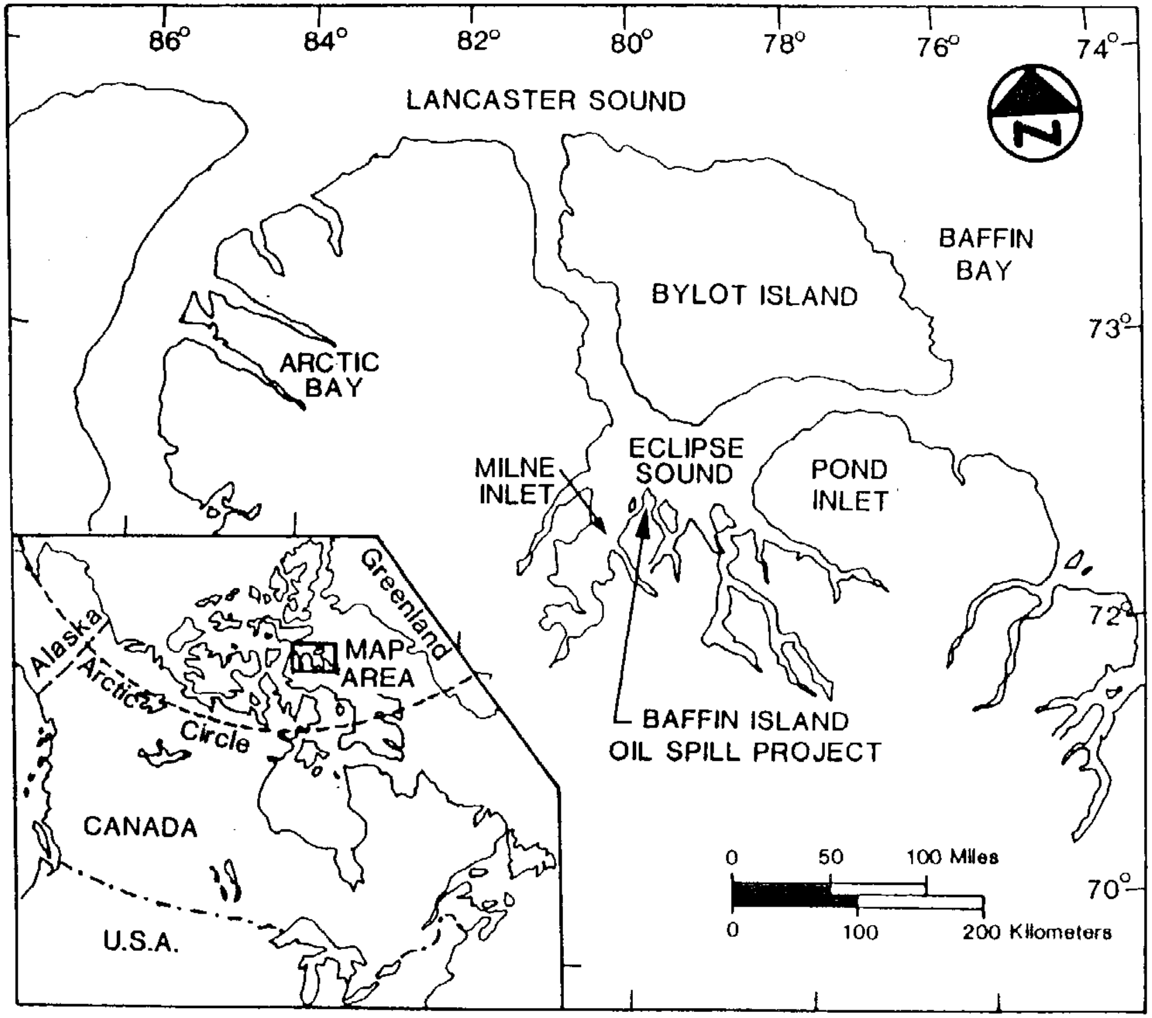

Figure 5.1. Location of the BIOS site and experimental plots.

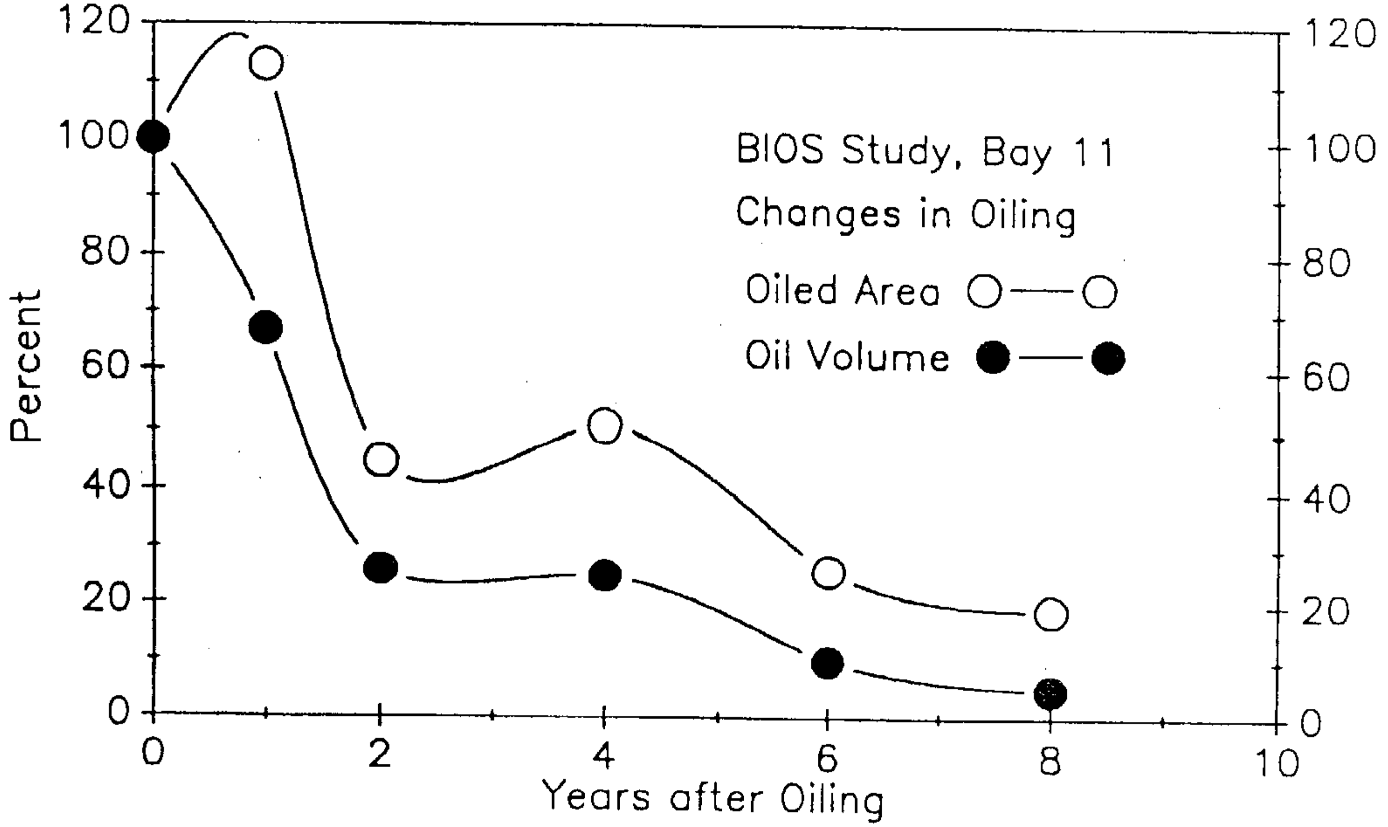

Figure 5.2. Plot of oil degradation over time at Bay 11 (from: Owens et al., pre-publication).

crude, the other with emulsified oil, in a sheltered intertidal area. By 1982, the emulsified plot showed very little oil remaining. On the aged crude plot, a minor amount of oil remained after three years, and less so in 1985. Chemical analyses, although showing normal variability, support the visual observations.

In 1981, a fairly large intertidal area (Bay 11 in Ragged Channel) was oiled as part of the test procedure to determine natural oil degradation within a sheltered, mixed sand and gravel beach. The site was approximately 300 m long and 32 m wide and doused with 30 bbl of Lago medio crude oil (Sergy and Blackall, 1987). Sediments were fully saturated. Results over four years of study (1981-1985) indicate that a substantial part of the oil remained within the environment, after an initial drop of approximately 50% during the first two years, based on oiled surface coverage. Surface coverage commonly overpredicts the amount of oil remaining. Owens et al. (1990, pre-publication) indicates that the oil volume remaining had dropped to 28% of the original amount by 1983. Subsurface oiling showed little change in mean concentration (900 mg/kg to 631 mg/kg) over four years.

In summary, these BIOS control site results show typical variability at a real spill site. At the small test plots at Bay 103, only minor amounts of oil remained after three years and less after five years. At the emulsified oil test site, oil was removed after two years. At the larger control site in Bay 11 in Ragged Channel oil, remained evident after eight years even though coloration changes made it more difficult to detect. After two years, approximately 28% of the original volume of material remained oiled contaminated; and after eight years, 5% (by volume) remained.

5.3.3 Treatment Test Plots

The studies discussed previously provide an overview of natural conditions of oil degradation at the BIOS site. In addition, several studies were carried out to measure effectiveness of various spill-treatment measures. As before, these have particular relevance to the EXXON VALDEZ site as some of these measures are being considered for application in Alaska.

Sediment discing or tilling is one procedure tested at BIOS, first in 1981 (Crude Oil Point) and again in 1982 (Bay 106) test plots.

At the 1981 (Crude Oil Point) test plots, oil was still visible as stained pebbles and cobbles at both the tilled and control test sites after four years. The test site did, however, retain a thick patch of oil, whereas the tilled site (understandably) did not. After year one, chemical analysis indicated slightly lower surface and subsurface values than for the controls, as would be expected from mixing the oil into a larger volume of sediment. However, after three years and continuing after five years, the tilled site still shows very high hydrocarbon values below the surface. A plausible explanation is that sediments were mixed below a depth of sediment reworking and that bacterial degradation was very limited.

At Bay 106 (Z lagoon), additional oiled plots were laid down in 1982 along the backshore in an area unaffected by marine processes. The purpose was to replicate oil stranded high on the beach after exceptionally high tides (as happened at the METULA site). One half of each plot was roto-tilled to test the results. At these sites, there appeared little chemical differences between control and tilled surface sediments (20,650 versus 19,475 mg oil/kg sediment) and subsurface sediments (5,524 versus 6,175 mg oil/kg sediment) after three years. Mixing was also found to have no long-term impact on the degree of evaporative weathering. The control site showed more (not less) microbial degradation than the tilled sites based on alkane/isoprenoid ratios. However, Owens et al. (1984) report that visually the tilled site appeared less oiled.

The conclusions reached by Owens et al. (1984) after reviewing the data on tilling versus controls at the BIOS site was that tilling had visual value if undertaken immediately after impact, but that after three years, it had little effect on reducing hydrocarbon concentrations.

5.4 SUMMARY

The experimental oiling BIOS program offers much data applicable to the EXXON VALDEZ site and is supported by observations at other spill sites. Oil degradation rates were found to be variable; one sheltered site showed almost complete natural cleanup after three to five years, while another showed extensive asphalt-pavement formation and less degradation after three years. Chemical analyses of oiled sediments supported the visual observation of oil removal and degradation. The role of bacterial degradation was apparently minor. It was also observed that tilling produced a better visual surface appearance with probable less oiling of mammals or fish utilizing the surface, but did not produce a more rapid, long-term degradation of either surface or subsurface oiling. On the negative side, tilling could cause the placement of oiled material below the zone of active sediment movement, thereby increasing the long-term persistence of oil within the beach.

5.5 INCLUDED REPRINTS

Owens, E.H., J.R. Harper, W. Robson, and P.D. Boehm. 1987. Fate and persistence of crude oil stranded on a sheltered beach. Arctic, vol. 40, pp. 109-123.

6.0 MISCELLANEOUS SPILLS

The spills described in this section are pertinent to the EXXON VALDEZ situation in that they occurred in areas with similar habitats. They provide various amounts of information on oil persistence, lasting ecological effects of the spilled oil, and effects of clean-up methodologies. The spills are organized in chronological order to show advancements in spill technology and monitoring as such methodologies are refined over the years. The TORREY CANYON spill is by far the most studied of all cases described in this section. It was not included in the major spills described earlier in this report because a very toxic dispersant was widely used throughout the oil-impacted area. This fact makes it difficult to compare the effects and persistence of TORREY CANYON oil to the current situation in Prince William Sound.

6.1 TORREY CANYON SPILL, WEST CORNWALL, ENGLAND (1967)

Southward and Southward (1978) provided a summary of the many studies on and effects of the TORREY CANYON spill. They reported that an estimated 14,000 tons of Kuwait crude oil stranded along 150 km of the coast of West Cornwall. This oil was treated with 10,000 tons of dispersant (usually 12% nonionic surfactant and 3% stabilizer in a kerosene extract) which proved to be extremely toxic to seashore life. The oil itself appeared not to have much of a toxic effect on rocky shores. It was difficult to determine exactly which areas had been affected by dispersant because much of the coast was re-coated by floating mixtures of oil and dispersant. Dispersant was also used indiscriminately in remote coves.

Dispersant-treated oil persisted on rocks for some months in some areas and it seemed not to weather more rapidly than untreated oil. Oil on rocky shorelines, whether treated or not, disappeared after one year. Oil driven into beach sand by dispersant treatment, buried by bulldozers, or covered by natural sand movements persisted for several years. Crude oil weathering rates slowed after it sank beneath the fully oxygenated layer on sand beaches. Oil in other areas lasted for varying lengths of time which were usually related to each area's level of protection from the open sea.

Southward and Southward (1978) provide a very detailed description of the ecological recovery of rocky shores for numerous sites spread throughout the oiled areas (Table 6.1). In general, recolonization of rocky shores involved a preliminary resettlement of algae followed by animals. The process was slow with a very protracted return to normal. Opportunistic species initially predominated and have only gradually been displaced by later colonizers. Biological communities on lightly oiled rocks, with moderate dispersant applications, required from five to eight years to recover while communities on heavily oiled rocks, which were also most affected by dispersants, required nine to ten years for recovery. Other areas were still not considered to be normal in 1978 at eleven years post-spill.

Table 6.1. The time course of recolonization of rocky shores in Cornwall, expressed in years from the date of the TORREY CANYON disaster, March 1967 (from: Southward and Southward, 1978).

	Lizard Pt. exposed (Vellan Drang)	Lizard Pt. sheltered (Polpeor Cove)	Porthleven west of harbor	Maen Du Pt. Perranuthnoe	Sennen Cove exposed (300 m east of pier)	Sennen Cove (near Pier)	Cape Cornwall (Porthledden side)	Trevone exposed ("sewer rocks")	Trevone sheltered (MTL reefs)
Relative exposure to wave action	+++	++	++	++	+++	++	+++	+++	+
Amount of oil stranded	+	++	+++	●	++	+++	++	++	+++
Dispersant treatment	(+)	+++	+++	(++)	++	+++	++	++	+++
Enteromorpha maximum[a]	1	1	1	1	0-1	1	1	0-1	1
Maximum *Fucus* cover	2-3	1-3	1-3	2-3	1-3	1-3	1-2	2	1-3
Minimum of barnacles	2	2	3	4	3	3	3	2	2-6
Maximum numbers of *Patella*	—[b]	6	5	5	—[b]	3	3	3	5
Fucus vesiculosus starts to decline	4	4	4	4	4	5	3	3	4
Fucus vesiculosus all gone	5	6-7	6-7	6	5	6	5	5	8
Increase in barnacles	4	6	6	5	4	6	4	3	7
Numbers of *Patella* reduced	—[b]	6	8	7	6-7	8	7	—[b]	6
Normal richness of species regained	5	9	10[c]	8-10	9	9	8-9	5-6	9-10[c]

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[a] Only Trevone could be visited often enough from Plymouth to be sure of the extent of the "greening" the 1st year.

[b] No quantitative data.

[c] Full richness of species probably not yet regained on the area surveyed.

( ) Dispersant treatment comparatively lighter than at other places given same score.

6.1.1 Included Reprint

Southward, A.J. and E.C. Southward. 1978. Recolonization of rocky shores in Cornwall after use of toxic dispersants to clean up the TORREY CANYON spill. J. Fish. Res. Board Can. 35:682-706.

6.2 SANTA BARBARA BLOWOUT, CALIFORNIA (1969)

Cimberg et al. (1975) summarized the initial spill reports and rocky intertidal beach surveys through 1972 for the Santa Barbara spill. Forty-five days after the spill, which occurred at the rate of 500 to 5,000 barrels per day, 100 miles of the Southern California coast line were contaminated by oil.

Oil had its greatest effect on rock pools and high exposed rocks within the Santa Barbara Channel. Surf grass (*Phyllospadix*) growing in tide pools was nearly completely coated and most was killed by this spill. Brown algae, with a heavy mucoid film, were not greatly affected by oil in the same tidal pools. Numerous species of algae attached to upper intertidal rocks were damaged or covered by oil. A small barnacle (*Chthamalus fissus*) in the intertidal suffered high mortality levels while larger barnacles (*Balanus glandula*) survived because they protruded through coatings of oil.

These authors concluded that oil mortalities were localized due to the nature in which oil moves in the intertidal. It was difficult to discern oil effects because of the complications caused by sand movement during severe storms and due to differences in substrate stability. Sand sheets commonly covered exposed rocks and smothered attached fauna while fauna attached to overturned boulders usually died.

6.3 IRINI OIL SPILL, STOCKHOLM ARCHIPELAGO, SWEDEN (1970)

The tanker IRINI ran aground and released about 1000 tons of medium and heavy fuel oil into the Stockholm Archipelago on 6 October 1970. An estimated 400 tons of this oil drifted into a small bay, Gastviken, where it almost completely killed the entire littoral fauna (Notini, 1978). The Swedish coast guard enclosed the oil within the bay by laying booms across the area. Much of the oil was then collected mechanically during November-December 1970. The final cleanup was done after all ice was gone. Oily sand was removed and rocks and stones were cleaned. Solvents were not extensively used. All cleanup efforts ended by the middle of May 1971. By June 1971 very few signs of the massive spill or newly finished cleanup operations were evident. Oil was still visible under the surfaces of sandy beaches and below stones. Subsequent analyses of oil collected from these areas showed that oil degraded much more rapidly on rocky shores than on sandy beaches.

Notini (1978) reported on the recovery of the littoral community during the period 1971-1976. No effects of the oil were detected on macroalgae during the summer and autumn of 1971. They continued to survive and prosper following natural patterns of succession throughout the study period. Littoral fauna were more strongly affected but recovered rapidly at various taxon-specific rates.

6.4 SAN FRANCISCO OIL SPILL, CALIFORNIA (1971)

Two Standard Oil tankers collided under the Golden Gate Bridge on 18 January 1971. The accident resulted in a spill of 840,000 gallons of Bunker C oil into San Francisco Bay. Tidal currents carried the oil to sandy beaches and shale reefs in nearby coastal areas. An initially large mortality of intertidal marine invertebrates was observed. Barnacles were smothered by oil. From 1972 to 1974 counts of invertebrates (especially snails, mussels, limpets, barnacles, and crabs) and the biomass of algae and seagrasses returned to, and in some cases surpassed, pre-spill levels (Chan, 1975).

6.4.1 Included Reprint

Chan, G.L. 1975. A study of the effects of the San Francisco Oil Spill on marine life. Part II: Recruitment. 1975 Conference on Prevention and Control of Oil Pollution, pp. 457-461. API Washington, D.C.

6.5 GENERAL M.C. MEIGS OIL SPILL, WASHINGTON (1972)

A long, gradual release of Navy Special fuel oil from the wreck of the unmanned troopship GENERAL M.C. MEIGS occurred over a five-year period from January 1972. Much of the oil was released as tar globules with the abundance and individual size of the tar balls decreasing over time.

Sea urchins (Strongylocentrotus purpuratus) were the first animals to show obvious damages from this unusual spill event. Many urchins lost spines and some lost most of their spines. This was not observed at unoiled control sites (Clark et al., 1978). Damaged urchins were found through July 1973 but were not seen on subsequent surveys. The abundances of live barnacles, mussels, and colonial anenomes steadily declined at oiled sites from March 1972 through January 1973; the abundances of barnacles increased by February 1977 but other species whose abundances originally declined remained at an unchanging low level. Four other species, including a second anenome, a limpet, an urchin, and a snail were not affected. No species of the 45 included in a checklist (Table 6.2) were known to have been eliminated from Wreck Cove (the site of the spill).

Oil from this spill has persisted on rocks above the normal tidal level because the initial grounding and spill occurred under near-hurricane conditions. The GENERAL M.C. MEIGS was under tow from Puget Sound to San Francisco when the storm struck. Oil has also persisted for various lengths under rocks in the intertidal zone. In some instances considerable degradation occurred during the first post-spill months while little change was seen when oil was collected from under a rock at 21 months post-spill. Tar globules were frequently combined with pebbles, rocks, sand, shell fragments, and plant fibers.

Table 6.2. Animal species present at sampling sites 1 through 15 in Wreck Cove on 20 January 1973, 27 July 1973, and 20 August 1974 (From: Clark et al., 1975).

PHYLUM Class *Species*	20 January 1973	27 July 1973	20 August 1974
COELENTERATA			
Anthopleura elegantissima	1-4	1-7	4,8
Anthopleura xanthogrammica	1-12	1-15	1-15
ECHINODERMA			
Henricia leviuscula	4	12,15	1
Leptasterias hexactis	3	4-15	1-15
Pisaster ochraceus	1-12	4-15	1,5,8-15
Pycnopodia helianthoides	---	---	---
Strongylocentrotus purpuratus	3-12	8-15	4-15
MOLLUSCA			
Amphineura			
Tonicella sp.	8	3,8,13	4,15
Cryptochiton stelleri	8	4,15	15
Katharina tunicata	1-12	4-15	1-15
Mopalia muscosa	8	---	---
Mopalia sp.	---	1,4,12	---
Nudibranchia	---	4,12	15
Pelecypoda			
Entodesma saxicola	8	12	---
Venerupis staminea	---	8,15	1
Mytilus californianus	1,3	1,3	1,3,5
Gastropoda			
Acmaea mitre	3	15	15
Calliostoma ligatum	8	---	15
Ceratostoma foliatum	---	12	---
Diodora aspera	---	---	8
Crepidula adunca	3	---	1,3,8
Crepidula sp.	---	---	---
Littorina scutulata	1,5	1,2,3,5,13	1-12
Littorina sp.	---	---	---
Megatebennus bimaculatus	3	---	---
Searlesia dira	1-3	1,8,15	1,2,8
Tegula pulligo	1-3	1-12	1,2,8
Thais emarginata	---	1,4	1,3,8,9
Thais lamellosa	---	---	15
Unidentified limpet	2-5	1,3,4,12,15	1-12
ARTHROPODA			
Balanus cariosus	1,3	1,3,4	1,3
Balanus nubilis	---	---	---
Chthamalus dalli	1-12	1,13	1,5
Decapoda			
Hemigrapsus nudus	---	1	1
Lophopanopeus bellus	---	1,8,15	---
Oedignathus inermis	13	---	---
Pachycheles rudis	13	---	13
Pagurus hirsutiusculus	---	---	---
Pagurus sp.	1-8	1-15	1-12
Petrolisthes cinctipes	---	---	1
Pugettia producta	8	2	4
Pugettia gracilis	---	12-15	4-13
Isopoda			
Idothea wosnesenskii	---	1,4	1
Amphipoda	---	5	1
CHORDATA			
Styela gibbsii	---	---	---

All of these materials were glued together into a brittle matrix. The chemical nature of the oil in this matrix had changed considerably since the spill.

After the MEIGS spill it was difficult to separate old spilled oil from freshly released oil since there was a persistent release of oil from the wreck for five years. The authors analyzed samples of the new tar balls and found them to bear a reasonable chemical similarity to the originally spilled fuel oil (Clark et al., 1975).

6.5.1 Included Reprint

Clark, R.C., Jr., B.G. Patten, and E.E. DeNike. 1978. Observations of a cold-water intertidal community after 5 yr of a low-level, persistent oil spill from the GENERAL M.C. MEIGS. J. Fish. Res. Board Can. 35:754-765.

6.6 TAMANO OIL SPILL, CASCO BAY, MAINE (1972)

The TAMANO, a Norwegian tanker, spilled 100,000 gallons of No. 6 fuel oil at the entrance channel into Casco Bay, Maine, on 22 July 1972. A local clean-up contractor was contacted after the ship reached its anchorage forty minutes after striking the ledge. Strong tidal currents in this bay spread the oil rapidly while the inability of the ship to dock in the shallow harbor hampered efforts to contain the spill.

Casco Bay intertidal areas are predominated by steep rock shelves, outcrops, and intrusions. Coarse-grained beaches and a few marshes are interspersed between rock outcroppings. The tidal range in this area averages 2.75 m. Offshore islands constrain tidal movement to channels between the islands; this results in fairly high water current velocities (Eidam, 1975). Casco Bay is a major recreation area for Maine and significant amounts of seafood (lobsters, shellfish, and seaweed) are harvested from its waters.

Much of the spilled oil was absorbed by seaweed which covers most of the bay's intertidal rocks. All heavily oiled seaweed beds were cropped to insure that large concentrations of oil in the weeds would not recontaminate other areas. Seaweed holdfasts were not removed in hopes that new growth would occur from these bases. Hot water (66-77°C) under high pressure (56-70 kg/cm^2) was used to clean rocks at public beaches and at other areas with distinct esthetic value. During cleanings booms were used to contain oil while sorbents were placed within boomed areas to absorb refloated oil. At sites further away from the spill area oil was usually mixed with floating debris before it beached. The oiled debris made it easier to clean these beaches.

Heavily oiled cobble beaches were more difficult to clean. Oil was initially deposited in a 3.0 to 4.5 m strip in the upper intertidal areas and rapidly penetrated into the underlying sand during low tides when air temperatures warmed the oil above its pour point. Penetration depths ranged from 10 to 30 cm (Eidam et al., 1975). Oiled sand was physically removed from these heavily oiled beaches in order to prevent contamination of other areas.

Ecological studies began soon after the spill and were based upon a design which utilized comparisons of oiled treatment and unoiled control sites. Intertidal mud flats which supported commercial shellfish beds were heavily impacted. Complete loss of intertidal mud flat fauna were recorded at one site and contamination of clams and contamination of sediments by No. 6 fuel oil were recorded at less severely affected sites. Gradual recovery towards normal faunal densities began soon after the spill.

Seaweed and barnacles were killed immediately in rocky intertidal areas and snails were killed in rocky coast tidal pools. Lobsters showed a slow increase in hydrocarbon burdens by the end of the first three-month post-spill period. In subtidal stations there was no initial decrease in population density but contaminated organisms showed a slow gradual build up of hydrocarbons followed by tissue degradation in some cases.

At one year the affected areas were studied again to determine the longer-term impact of the spill (Eidam et al., 1975). Intertidal mud flats were still strongly affected with no evidence of new recruits. A new set of shellfish did occur in the control sites. Intertidal seaweeds on rocky shores actually did best in areas where oiled fronds had not been removed. Regrowth occurred in the cropped areas but not as heavily as in uncropped areas. Fauna normally associated with the seaweeds were still reduced in abundance in the cropped areas. Hot water cleaned areas in the upper intertidal showed slower recolonization rates than in areas that were not cleaned. Part of this effect was attributed to heavy human traffic in the upper intertidal since hot water cleaned lower intertidal areas fared much better. Communities on lower intertidal rock surfaces and in tidal pools were more diverse in cleaned areas than in heavily oiled, uncleaned areas. The lasting ecological effects of oiled sand and rock removal were not discussed.

6.6.1 Included Reprint

Eidam, C.L., E.V. Fitzpatrick, and J.F. Conlon. 1975. The Casco Bay oil spill: problems of cleanup and disposal. Proc. 1975 Conference on Prevention and Control of Oil Pollution, pp. 217-221. EPA/API/USCG Washington, D.C.

6.7 KURDISTAN OIL SPILL, CABOT STRAIT, NOVA SCOTIA (1979)

The tanker KURDISTAN, during a severe storm, suffered major damages to its hull and spilled about 7,000 tons of Bunker C crude oil into ice-infested Cabot Strait (Duerden and Swiss, 1981). The ship soon split in two. The bow and stern sections remained afloat. The bow section, which still contained 7,000 tons of oil was later towed out to sea and sunk by naval gunfire. The stern section was towed to a safe harbor where its 16,000 tons of fuel oil were unloaded.

Oil spilled from the KURDISTAN was difficult to track because of bad weather and ice interference with tracking systems (Duerden and Swiss, 1981). The oil floated below the surface and made it necessary to wait until the oil beached before attempting to collect it. An assessment of shoreline sensitivity was made before the oil beached to determine where protection and clean-up efforts should be centered. The areas surveyed during this reconnaissance included Chedabucto Bay where the Arrow oil spill occurred in 1970.

Duerden and Swiss (1981) reported that the most conspicuous victims of this spill were birds. According to these authors there were no long-term impacts despite the fact that coastlines throughout the region were oiled or re-oiled as subsurface floating oil unexpectedly emerged.

6.8 TANIO OIL SPILL, BRITTANY (1980)

The TANIO oil spill occurred on 7 March 1980 off the coast of Brittany, France, affecting 45% of the AMOCO CADIZ area (Berne, 1980; Gundlach et al., 1981). The oil type was a heavy, No. 6 fuel oil, notably black in color. Shore types affected were sand beaches, sand/gravel shores and tidal flats, and bedrock. Cleanup used the same washing, high-pressure hosing, and hot-water blasting (of rocks in tourist areas), as undertaken during the AMOCO CADIZ spill two years previous.

Surveys undertaken by Fichaut in 1983 and Gundlach in 1985 as part of the AMOCO CADIZ litigation found remnants of the TANIO spill along high-energy gravel shores, present as 1) tarry blotches or stain on rock surfaces, 2) as asphalted layers above the active intertidal zone, and 3) as mobile oil in a limited number of sheltered, coarse-grained (coarse sand/fine gravel) sediments. The persistence of mobile oil in the sediments after five years is notable (see photographs in Figures 6.1 and 6.2).

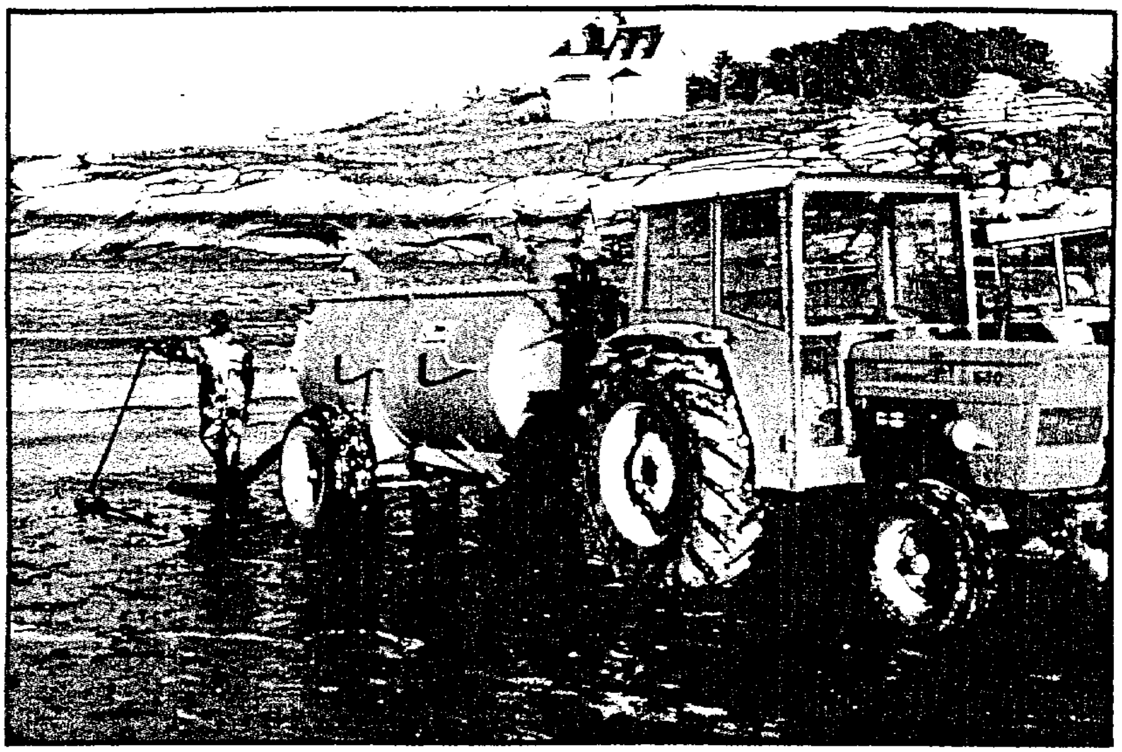
6.9 KATINA OIL SPILL, PROVINCE OF SOUTH HOLLAND (1982)

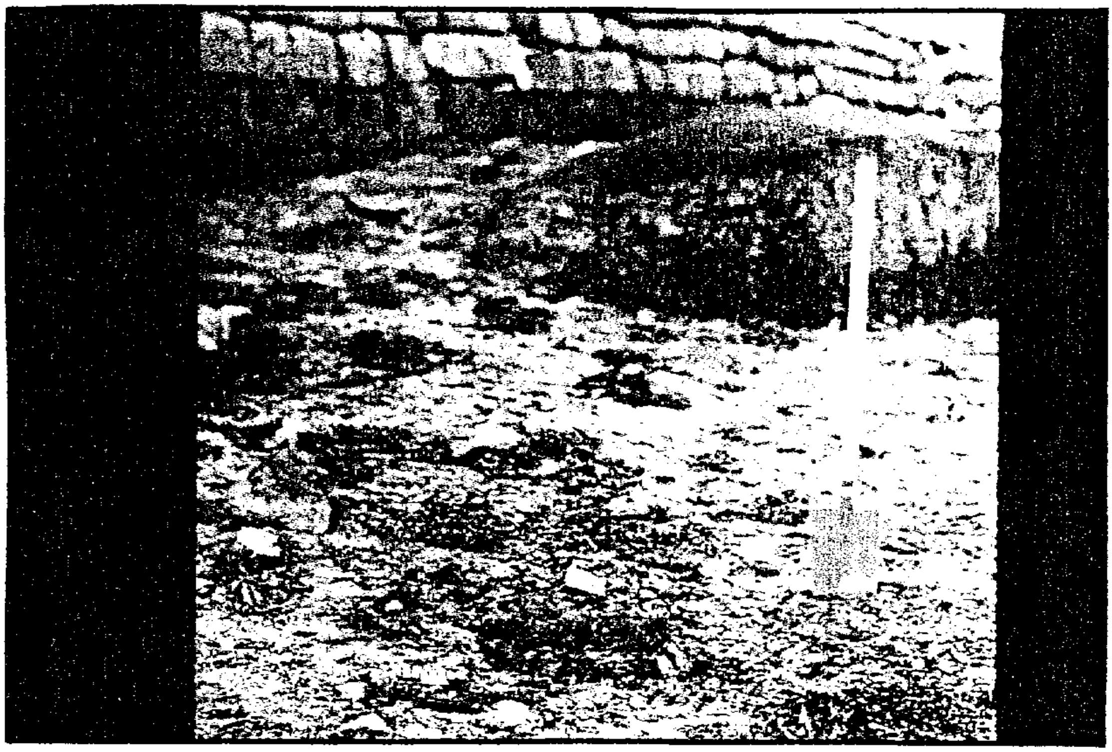
A collision between the tanker KATINA and an ore freighter, the PENGALL resulted in a spill of 1,600 m^3 of crude oil into the North Sea. Descriptions of cleanup operations at sea (Koops et al., 1985) and on oiled beaches (Kleij and Gubbens, 1985) describe the efforts made to reduce the impact of this oil spill.

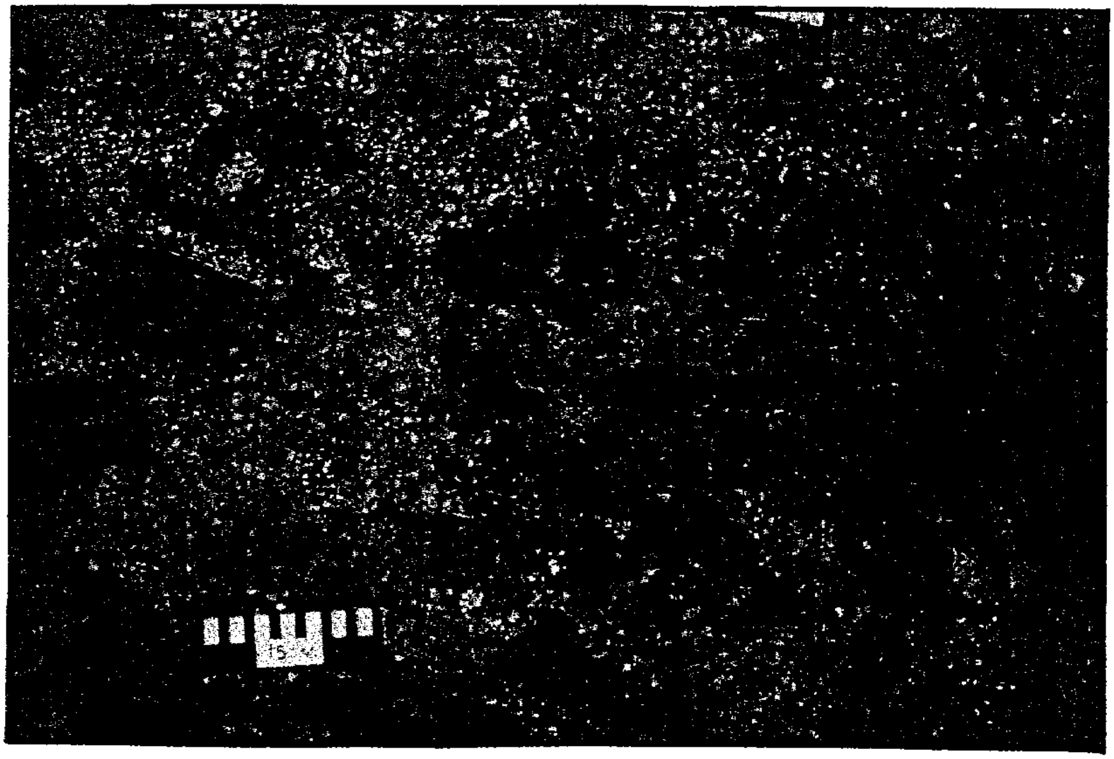
Most of the beaches in this area are sand. Sand was removed and sieved to remove most of the oil. Lightly oiled sand was later buried on the same beaches with the expectation that the little oil that remained would be removed by biological processes. Oil that remained after sieving was burned.

6.10 SIVAND OIL SPILL, HUMBER ESTUARY, UNITED KINGDOM (1983)

The tanker SIVAND spilled 6,000 tons of Nigerian Forcados crude oil into the highly turbid Humber Estuary on 26 September 1983. Fate of this oil is described by Little (1987). Much of the oil penetrated



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marsh sediments through root macropores in saltmarshes. This oil remained as an important source of fresh oil after other oiled sites were cleaned. Descriptions of the ecological effects of the SIVAND spill (Mitchell et al., 1985) deal with organisms from habitats that are not found in Prince William Sound, Alaska. Birds and mudflat invertebrates, principally polychaete worms, were the most obvious victims of this spill. Concerns were expressed about surviving birds consuming carcasses of invertebrates killed and presumably contaminated by oil.

6.11 ARCO ANCHORAGE SPILL, PORT ANGELES, WASHINGTON (1985)

The tanker ARCO ANCHORAGE spilled 239,000 gallons of Alaska North Slope (ANS) crude oil into Port Angeles, Washington, on 21 December 1985. Approximately 2,150 m of the south-facing shore of Ediz Hook were subsequently oiled. This sheltered shore is composed of sand and gravel sediments extending from intertidal to subtidal areas. Bulldozers with ripper teeth and a water jet systems were used to agitate beach sediments. This action reduced beach sediment oil concentrations from 2,240 ppm to 670 ppm (Miller, 1989). A monitoring program, initiated after the beach agitation program ended, found a steady decline of oil concentrations in both intertidal and subtidal areas through 1988. Despite the observations that much of the beach in this area is highly sheltered and is rarely affected by episodes of sand transport, all signs of beach agitation were gone by May 1988.

Port Angeles is a highly industrialized area; this fact made it difficult to discern the effects of the ANS crude spill on benthic infauna in that it may have limited recovery and recolonization of oiled sediments (Blaylock and Houghton, 1989; Mancini et al., 1989). An infaunal monitoring program began in 1986 after the cessation of beach reclamation activities. Control (unoiled areas) were monitored for comparison to numerous oiled sites. ANOVAs on infaunal densities and correlations of oil concentrations to infaunal counts were the major methods of analysis applied to these data. ANOVAs showed a steady increase in biomass, abundance, and diversity over time at several heavily oiled sites (Blaylock and Houghton, 1989). A similar pattern was not seen at an unoiled reference station. Correlations showed a negatively significant pattern of increasing abundances with decreasing oil concentrations (Mancini et al., 1989). Due to low residual ANS crude oil concentrations it was suspected that by 1988, on the last survey reported by Blaylock and Houghton (1989), that pre-spill conditions had been attained.

6.11.1 Included Reprints

Blaylock, W. M. and J. P. Houghton. 1989. Infaunal recovery at Ediz Hook following the ARCO ANCHORAGE oil spill. Proc. 1989 Oil Spill Conference, pp. 421-426. USCG/API/EPA Washington, D.C.

Miller, J. A. 1989. Physical and chemical recovery of intertidal and shallow subtidal sediments impacted by the ARCO ANCHORAGE oil spill, Ediz Hook, Washington. Proc. 1989 Oil Spill Conference, pp. 487-491. USCG/API/EPA Washington, D.C.

6.12 CABO PILAR OIL SPILL, PUNTA DAVIS, MAGELLAN STRAIT, CHILE (1987)

The tanker CABO PILAR spilled 5,200 m^3 of crude oil into the Magellan Strait at Punta Davis on 8 October 1987. This area is a considerable distance from the site of the grounding of the METULA (Section 3.0, this report) but the brief description of shoreline given in Pizaro (1989) suggests that the affected shores are similar.

The oil slick was initially treated with dispersant from a supply vessel and attempts were made to contain oil in boomed sidebays on this very complex waterway. Pizaro (1989) offered only very sketchy descriptions of the initial ecological effects of this spill. Rock and stone beaches were oiled and seaweeds were extensively killed but oiled beaches were seen to be improving after six months. King crabs, the main economic resource of this area, did not seem to be affected.

6.13 AMAZZONE, BRITTANY (1988)

On 31 January 1988, the coast of Brittany was once again hit by an oil spill. In this case it was about 1500 tons of a highly paraffinic medium fuel oil from the AMAZZONE. Concerns were raised in the attempt to clean cobble/pebble beaches, particularly after the AMOCO CADIZ which produced mixed-to-negative results when sediments were moved. As a result a large-scale washing plant was moved in for testing (Huet et al., 1989). Testing occurred using water washes of varying temperatures and with the addition of a petroleum cut and surfactant. Temperature tests were limited to 17°C or less, due to equipment limitations.

Results of the tests indicated that water of higher temperature was better than cold water but still insufficient to fully clean the rocks. With warm water and petroleum cut and surfactant, oil removal from the rocks was good, but there was insufficient rinsing so the pebbles remained coated. With further modification and testing of the device, it is likely that it would operate successfully. Costs of the operation were estimated at $50 per cubic meter of pebbles, not including transport to the cleanup site.

6.14 NESTUCCA OIL SPILL, GRAY'S HARBOR, WASHINGTON (1988)

The barge NESTUCCA spilled 875,000 l of Bunker C oil into coastal waters near Gray's Harbor, Washington, on 22 December 1988. The barge was initially towed further out to sea in hopes that the leaking oil would move away from nearby ecologically sensitive shorelines. Nearshore currents, onshore winds, and tidal currents moved the oil slick northward and toward the coast. This lead to the worst case of oil pollution along the west coasts of Washington and Vancouver Island, British Columbia currently on record (Waldichuk, 1989).

Oiled sand and gravel beaches were removed and replaced with fresh sand and gravel by the Canadian Coast Guard. Thousands of birds were killed and wolves were seen scavenging bird carcasses from oiled beaches (Waldichuk, 1989). At the present time more precise descriptions of the ecological impacts and recovery from these impacts are not available.

7.0 CONCLUSIONS

Some primary conclusions can be reached from the review of oil persistence and ecological recovery as observed at other oil spills:

1. There is a tremendous variation in oil spills, in the persistence of oil along seemingly similar environments, and in biological impacts among and between habitat types.

2. Oil degradation or removal from the shoreline by natural and/or man-made processes proceeds rapidly at first, slowing down over the period of years, with relatively isolated pockets of asphalt or oil-soaked sediments remaining after several years.

3. Asphalt crust or pavement is the most common form of persistent oil in the environment after an oil spill.

4. Asphalt crust or pavement forms in coarse-grained or mixed sediments (sandy gravel/cobbles, etc.) where oil has mixed into the sediments.

5. The most common locality for asphalt persistence is along the backshore, and to a lesser extent, along the upper low-tide terrace.

6. Crusts or pavements have persisted for over 12.5 yr at the METULA site and for longer at the ARROW site.

7. Relatively undegraded liquid or fluid oil has remained in isolated localities for longer than 3 yr after AMOCO CADIZ and more than 5 yr after the TANIO spill, where oil-saturated sediments were not naturally or manually flushed of heavy oil concentrations.

8. Within mud-dominated sediments, oil persisted longer than eight years at the AMOCO CADIZ site.

9. At AMOCO CADIZ sites where oil was allowed to enter the sediments below the zone of sediment movement through cleanup pits, trenches, or the use of heavy machinery on oiled tidal flats, oil persisted longer than eight years with little degradation.

10. A very degraded oil was found along the upper berm of well-flushed sediments in Patagonia, 6.5 yr after the METULA spill, apparently similar to test plots at the BIOS site in Canada.

11. Tilling has reduced surface concentrations at the BIOS site but has not reduced overall concentrations, and has possibly increased oil persistence by pushing in oil below the depth of active sediment movement.

12. Mechanical reworking of the beach has produced mixed results. On active beaches where sediments where pushed lower but remained on the beach face, oiled sediments were naturally cleaned and returned to the beach. However, in cases where oiled sediment was placed lower, as on the low-tide terrace below the active zone of sediment movement, the

gravel were cleansed but never returned to the beach face, with subsequent loss of shoreline protection against backshore erosion.

13. The reduction of heavy oil concentrations from the surface and subsurface assists the natural recovery of the site, reduces oil persistence, and lessens the likelihood of asphalt pavement formation.

14. The longest term biological effects have been found in soft sediments in shallow protected waters.

15. It is necessary to establish a rigorous and generally acceptable definition of ecological recovery. Recovery should only be claimed when an area has returned to its pre-spill conditions (which is often not known except through comparisons to nearby unaffected sites) as defined as being fully occupied by its pre-spill fauna and flora. An alterative definition is that recovery could be claimed when post-spill productivity is equivalent to pre-spill levels. This is a much less rigorous definition since the organisms present in the post-spill habitats may be completely different than before the spill.

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A-4

Residues of Bunker C Oil in Chedabucto Bay, Nova Scotia, 6 Years After the *Arrow* Spill[1,2]

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KEIZER, P. D., T. P. AHERN, J. DALE, AND J. H. VANDERMEULEN. 1978. Residues of Bunker C oil in Chedabucto Bay, Nova Scotia, 6 years after the *Arrow* spill. J. Fish. Res. Board Can. 35: 528–535.

The *Arrow* spill in February 1970 heavily oiled approximately one half of the 600 km shoreline of Chedabucto Bay, Nova Scotia. An extensive field survey and chemical analysis of sediment samples for aliphatic and polycyclic aromatic hydrocarbons identified only a few locations where *Arrow* Bunker C remained in the intertidal and sublittoral sediments. The upper intertidal zones of Rabbit, Crichton, and Durell islands remain covered with an oil and sediment mixture of a "pavement-like" consistency. Several areas showed visual and chemical evidence of recent spills during the survey period. All sublittoral sediment samples contained hydrocarbons of petroleum origin. The distribution of the most highly contaminated sublittoral sediments suggests either reentry of stranded oil into the water column and into the sublittoral sediments or contamination from shipping and fishing vessels. Concentrations in the sublittoral sediments are below those found toxic to benthic organisms. An estimation of the amount of Bunker C remaining in Chedabucto Bay is impossible due to the patchy distribution, contributions of more recent spills, and the absence of adequate control sites.

Key words: Bunker C, oil spill, Chedabucto Bay, gas–liquid chromatography, fluorescence spectroscopy, *n*-alkanes, polycyclic aromatic hydrocarbons

KEIZER, P. D., T. P. AHERN, J. DALE, AND J. H. VANDERMEULEN. 1978. Residues of Bunker C oil in Chedabucto Bay, Nova Scotia, 6 years after the *Arrow* spill. J. Fish. Res. Board Can. 35: 528–535.

A la suite du déversement de l'*Arrow* en février 1970, environ la moitié des 600 km de ligne de rivage de la baie Chedabouctou, Nouvelle-Ecosse, fut recouverte d'une épaisse couche de fuel-oil. Un relevé détaillé sur le terrain et l'analyse chimique des sédiments en vue d'y déceler la présence d'hydrocarbures aromatiques aliphatiques et polycycliques ne révélèrent que quelques endroits où il restait encore du fuel de soute C de l'*Arrow* dans les sédiments intertidaux et sublittoraux. Les zones intertidales supérieures des îles Rabbit, Crichton et Durell sont encore recouvertes d'un mélange de fuel-oil et de sédiments à consistence de « pavage ». Lors du relevé, on a pu constater à l'oeil et à l'analyse chimique les preuves de déversements récents. Tous les échantillons de sédiments sublittoraux contiennent des hydrocarbures d'origine pétrolière. La répartition des sédiments sublittoraux les plus fortement contaminés suggère soit l réentrée de pétrole échoué dans la colonne d'eau et dans les sédiments sublittoraux, soit la contamination provenant des navires de transport et des bateaux de pêche. Les concentrations trouvées dans les sédiments sublittoraux sont inférieures à celles qui sont toxiques pour les organismes benthiques. Il est impossible d'estimer la quantité de fuel de soute C qui demeure dans la baie Chedabouctou à cause de sa distribution irrégulière, des apports de déversements ultérieurs et de l'absence d'endroits témoins adéquats.

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THE Liberian tanker *Arrow*, carrying a cargo of 108 000 barrels (1.75×10^6 L) of Bunker C fuel oil, ran aground on Cerberus Rock in Chedabucto Bay, Nova Scotia, on February 4, 1970. Over the next several days an estimated two thirds of her cargo was released into the Bay. Oil slicks, driven by wind, currents, and tides, coated more than one half of the 600 km of shoreline (Anon. 1970). Large quantities of oil in the form of surface slicks and oil droplets in the water column were swept from the Bay by tides and currents (Forrester 1971). Concentrations of total oil in the water column were as high as 100 ppb in May 1970 (Levy 1971).

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[1] This paper forms part of the Proceedings of the Symposium on "Recovery Potential of Oiled Marine Northern Environments" held at Halifax, Nova Scotia, October 10–14, 1977.

[2] Bedford Institute of Oceanography Contribution.

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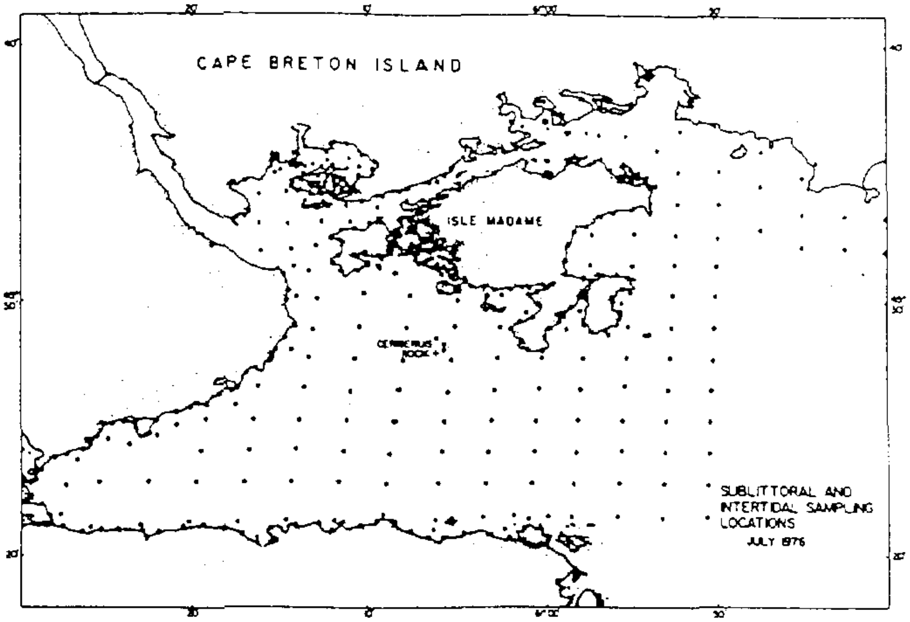

FIG. 1. Location of intertidal and sublittoral sampling stations in Chedabucto Bay, N.S.

By April 1971 concentrations of oil in the water column had dropped to a background level of <2 ppb (Gordon and Michalik 1971). By October 1973 much of the oiled shoreline had been cleaned by natural forces (Owens and Rashid 1976). Physical and chemical analyses of stranded oil suggested that the remaining oil would persist for many years (Rashid 1974; Vandermeulen and Gordon 1976). In 1975 Vandermeulen and Gordon (1976) studied the dynamics of oil movement in a lagoon contaminated with *Arrow* Bunker C and concluded that the areas of prime interest were the sediments and interstitial waters.

As part of a comprehensive study designed to evaluate the long-term effects of the *Arrow* spill, we have conducted an extensive survey of surficial sediments, intertidal and sublittoral, of Chedabucto Bay in July 1976. Using a variety of methods, we analyzed sediments for petroleum hydrocarbons in order to determine the distribution and chemical fate of the remaining spilled oil.

Materials and Methods

SAMPLING

Sublittoral — A van Veen grab was used to obtain samples of surficial sediment from 137 of the 165 locations shown in Fig. 1. The Strait of Canso area was not sampled due to the high probability of petroleum pollution from ship traffic and industry in this area. It was not possible to obtain samples at some locations due to the rocky nature of the substrate. The grab was thoroughly cleaned to remove grease and oil deposits before use and samples were removed from the middle of the grab to minimize the probability of contamination. Subsamples were placed in glass jars and sealed with foil-lined caps.

Intertidal — Sampling points were located approximately every 1.5 km along the shore (Fig. 1), and more frequently in areas where oil was still visible. Each of the 266 locations was surveyed for about 100 m on either side of the sampling point and the occurrence of any visible oil residues in the intertidal zone was noted. A mixed-sediment sample from the top 10 cm was obtained by removing a shovel of sediment and then sampling from the exposed surface opposite the shovel. Samples, collected from low, mid-, and high tide at each location, were placed in glass jars with foil-lined caps.

All samples, sublittoral and intertidal, were collected between July 5 and July 21, 1976 and frozen at −20°C within 6 h of collection. Sample containers and foil liners had been prerinsed with redistilled methylene chloride.

One intertidal site was sampled more intensively to determine the composition and distribution of hydrocarbons in the intertidal zone. The study site, an oiled beach in Moussiliers Passage, has been used in previous studies (for full description see Vandermeulen and Gordon 1976). It is a gently sloping beach, with sand to gravel at the high tide line changing to fine sand and silt along the low tide line, and forms part of Haddock Harbour, a large low-energy lagoon. A 2–3-cm thick tar layer lies along the upper high tide line.

Sediment samples were collected in duplicate from high, mid-, and low tide lines, in April 1976 and June 1977. On the first date, samples were collected in glass jars; on the second, cores were taken and frozen within 3 h.

ANALYTICAL PROCEDURES

Samples were partially thawed and subsamples were placed in preextracted glass Soxhlet thimbles and extracted for 18 h with 250 mL of methanol–benzene (2:3 vol/vol) (Fig. 2). After cooling, the extract was washed with 1 N HCl saturated with NaCl and the benzene layer was separated. The aqueous layer was extracted twice with 75

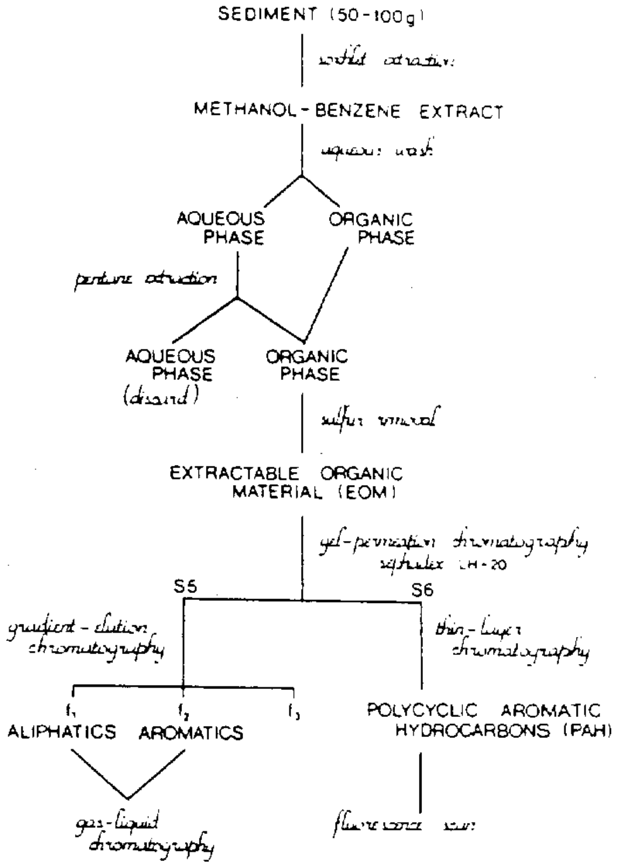

FIG. 2. Flow chart of analytical procedure. Details are given in the text.

mL of pentane and the combined benzene and pentane extracts were washed again with the acidic saturated salt solution. The organic layer was separated and dried over anhydrous Na_2SO_4 overnight. The extract was decanted into a Kuderna-Danish concentrator and reduced to 10 mL in volume. After sulfur removal (Blumer 1957) an aliquot was evaporated to dryness and weighed on an electrobalance to determine the concentration of extractable organic material (EOM).

The sample, or an aliquot (maximum of 20 mg EOM), was evaporated almost to dryness under a stream of nitrogen and the benzene was replaced with isooctane. Tetrahydrofuran (THF) was used to elute the sample from a column of 5 g of Sephadex LH-20 (12 × 170 mm). A fraction (S5) containing the *n*-alkanes and another fraction (S6) containing a group of polycyclic aromatic hydrocarbons (PAH) including benzo[*a*]pyrene (Hsieh et al. 1969) were isolated.

Separation of the PAH's from S6 was carried out on a cellulose plate dipped in 20% dimethylformide (DMF) in diethyl ether and developed with isooctane (White and Howard 1967). Aliquots of the PAH fraction from S6 of *Arrow* Bunker C samples and benzo[*a*]pyrene were spotted with the sediment extracts. The developed plate was observed under long wavelength ultraviolet light and then scanned at excitation/emission wavelengths of 271/362 and 365/445 nm on a Perkin-Elmer MPF-2A fluorescence spectrophotometer equipped with the thin-layer scanning accessory. Care was taken at all steps to minimize exposure of the plate to light.

Fractions S5 and S6 from the gel-permeation chromatography were concentrated under a stream of nitrogen and the THF was replaced with isooctane. Samples were then chromatographed on a column of alumina on silica gel (1:1 wt/wt, 5 × 70 mm) eluting with pentane ("aliphatics"), 10 and 20% benzene in pentane ("aromatics"), and benzene. Aliquots of each fraction were evaporated to dryness and weighed.

Aliquots of aliphatic fractions were injected onto a 15 m × 0.5 mm ID stainless steel SCOT column which was held at 100°C for 1 min, then programmed at 8°C/min to 280°C and held. Carrier-gas flow was at a constant pressure of 0.3 kg/cm² (~4 mL He/min at 100°C). Core samples were analyzed on a 25-m OV-101 glass capillary column. The injector, an MS-41 sampling accessory, was at 250°C; the flame ionization detector was at 350°C. Chromatograms were recorded and peak areas determined with a Hewlett-Packard 3380A Integrator. Areas for the unresolved complex mixture (UCM) were determined with a planimeter and concentrations determined by calibration with the UCM for a sample of *Arrow* Bunker C.

All solvents were reagent grade, redistilled in glass, except pentane which was practical grade, redistilled twice in glass. Thin-layer plates were 250 μm cellulose MN300 obtained from various suppliers. Silica gel was Hi-Flosil, 60/200 mesh, activated at 250°C for 18 h; alumina was Alcoa alumina F-20, 80/200 mesh, activated at 400°C for 18 h. Both supports were deactivated with 5% water (wt/wt). Activated copper, Na_2SO_4, silica gel, and alumina were all preextracted with solvent before use.

Results and Discussion

INTERTIDAL SEDIMENT SAMPLES — VISUAL OBSERVATIONS

Oil, presumably from the *Arrow*, still remains in the intertidal sediments in many areas of Chedabucto Bay. On the southern and western shores of the Bay, only the area around Durell Island remained heavily oiled (Fig. 3). Oil mixed with sand, gravel, and rocks in a "pavement-like" consistency covers the upper half of the intertidal zone in most of the sheltered locations in this area. There was also evidence of recent spills of light fuel oils. There is considerable ship movement in the area by inshore and offshore fishing vessels to and from the local fish plant at Canso which may be responsible for these spills. Owens and Rashid (1976), based on aerial observations, reported almost complete removal of oil from these shores by October 1973, the extent of oiling reported for the Durell Island area being somewhat less than noted in July 1976. The method of observation and/or accumulation from more recent spills may account for this difference.

The northern shore was the most heavily oiled area at the time of the *Arrow* spill. In July 1976, only an occasional patch of oil remained on the exposed northern coast with the exception of Crichton Island, the adjacent shoreline of Bonhomme Cove and the In-

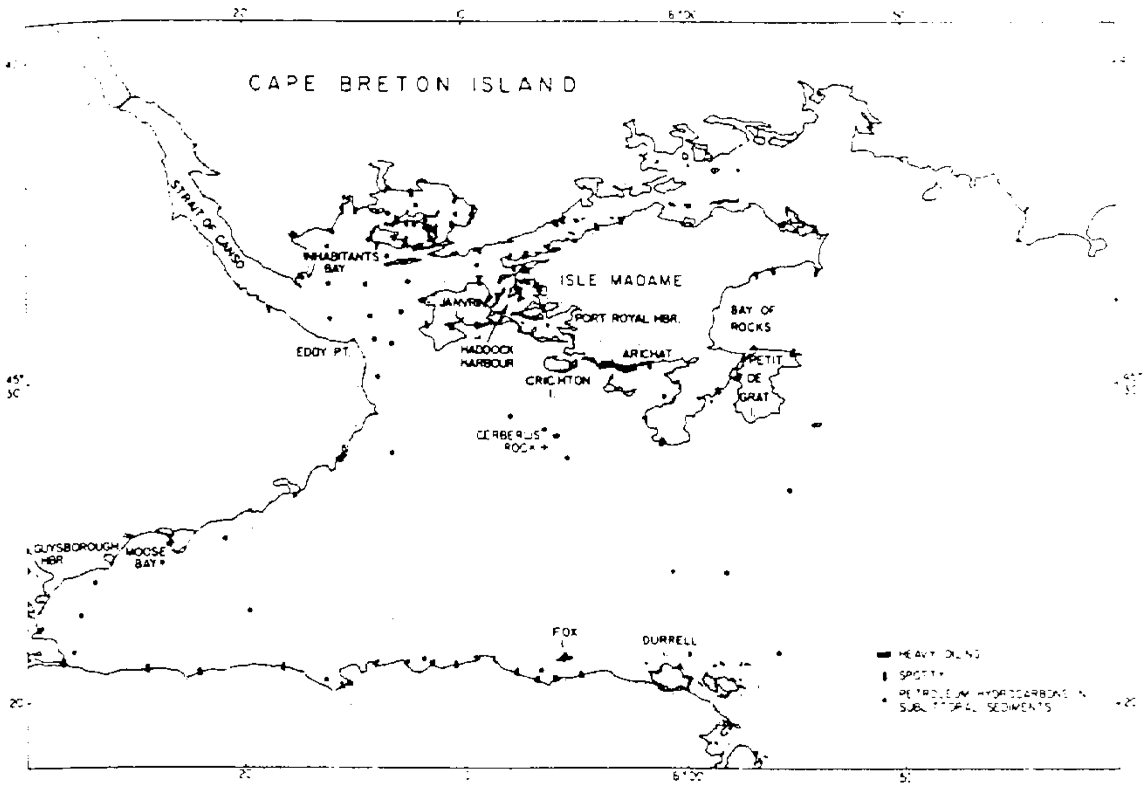

FIG. 3. Extent of oiling in intertidal and sublittoral sediments of Chedabucto Bay, July 1976.

TABLE 1. Concentrations of "oil" in intertidal sediments from Moussiliers Passage based on gas-chromatographic analysis. T1 and T2, transects 1 and 2.

		µg Bunker C g sediment[a]		
			June 1977	
Location	Depth (cm)	April 1976	T1	T2
High tide	2–5	67	110	24
	7–11	625	148	26
	12–15	1200	43	19
Mid-tide	2–5	106	36	129
	7–11	1280	25	145
	12–15	27	12	41
Low tide	2–5	155	442	821
	7–11	10	15	12
	12–15	7	41	11

[a] Based on the area of the UCM using *Arrow* Bunker C fuel oil as a standard.

habitants Bay area (Fig. 3). In the sheltered areas of Haddock and Port Royal harbors, there is little oil evident on the surface of the sediments; however, oil mixed with coarse sand and gravel was found in layers several centimetres thick, 5–10 cm below the surface in several locations. This oiled layer often extended from high to low tide but tended to be very patchy. It is therefore impossible to estimate the amount of oil that may be incorporated into the sediments of the area. Aerial observations in 1973 (Owens and Rashid 1976) did not reveal the presence of any oil in this area, although it had been heavily oiled at the time of the spill. This area is also frequented by small fishing and pleasure boats which may be responsible for some of the oil residues.

The shores of Rabbit Island in Inhabitants Bay and the adjacent point on the mainland are visibly the most heavily oiled areas remaining in Chedabucto Bay. "Pavement," up to 15 cm thick, covers much of the upper half of the intertidal zone and on hot days oily films spread out among the rocks onto the waters of the Bay. The extent of oiling on the remaining shoreline and the other islands of Inhabitants Bay and Inhabitants Harbour has diminished greatly since October 1973. Only the eastern and western ends of Evans Island remain heavily oiled, while only scattered patches of "pavement" remain on the rest of the shoreline. Occasionally, deposits of a subsurface oil and sand mixture were uncovered in this area, but as in the Haddock and Port Royal Harbour area the distribution was patchy.

Concentrations of Bunker C fuel oil, based on

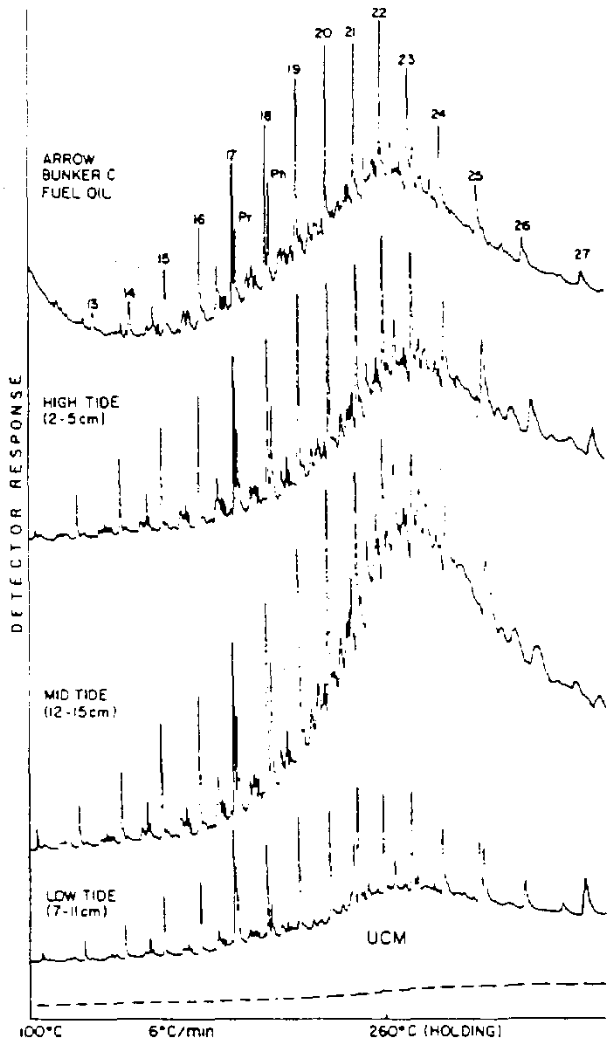

FIG. 4. Gas-liquid chromatograms of the aliphatic fraction of *Arrow* Bunker C fuel oil and sediment extracts from Moussiliers Passage. The broken line is a procedural blank; numbers above peaks indicate the number of carbons in the corresponding *n*-alkanes; Pr is pristane and Ph is phytane.

measurement of the UCM, varied by 2 orders of magnitude at the Moussiliers Passage study site (Table 1). The data suggest removal of the "oil" from the high tide zone with accumulation in the low tide sediments; however, the composition of the saturate fraction suggests another explanation for this apparent change. In April 1976 chromatograms of the saturate fraction revealed only a few minor resolved peaks on a large unresolved envelope, typical of a weathered residual fuel oil. Little difference was observed among the samples. However, samples collected in June 1977 were quite different. Many of the chromatograms (Fig. 4) exhibited a series of *n*-alkanes in the nC_{14}–nC_{22} range superimposed on the unresolved envelope, a pattern similar to that of a fresh No. 2 fuel oil. This is a definite indication that a light fuel oil had been spilled in the study area sometime near the sampling date. Therefore more than one spill of fuel oil has probably contaminated this area since the grounding of the *Arrow*. Once a crude or fuel oil has weathered, the unresolved envelope that remains is no more characteristic of *Arrow* Bunker C than any other oil. Because the source of petroleum-derived hydrocarbons in the sediments is not only *Arrow* Bunker C, it is impossible to evaluate the extent of weathering and the mobility of the stranded oil on the beach. This observation must also serve as a caution in interpreting data obtained from other sampling locations, intertidal and sublittoral.

SUBLITTORAL SEDIMENT SAMPLES

Gravimetric data — Concentrations of extractable organic material (EOM) in sublittoral sediments ranged from 5 to 2092 μg/g of dry sediment. The lower values are associated with coarse-grain sediments, the higher values with fine-grain sediments and sediments collected near more heavily populated areas such as Arichat Harbour, Durell Island, and Petit de Grat Inlet. These concentrations of EOM are generally higher than in offshore sediments in this area (Keizer et al. 1978) but of the same order of magnitude as samples from other inshore areas (e.g. Farrington and Tripp 1978). There is no evidence of a massive oiling of the sediment where 25–50% by weight may be extractable organic material.

Polycyclic aromatic hydrocarbons (PAH) — The composition of the PAH fraction of petroleum is substantially different from that of biogenic hydrocarbons. The PAH fraction in unpolluted marine sediments is dominated by the unsubstituted hydrocarbons or derivatives with low alkyl content, while in crude and Bunker C fuel oils, hydrocarbons with a greater alkyl substitution dominate (Youngblood and Blumer 1975). No attempt was made to isolate and determine concentrations of individual PAH's. The general composition of the PAH fraction should be an indicator of the presence of petroleum hydrocarbon residues.

Thin-layer chromatography of the PAH fraction of *Arrow* Bunker C fuel oil did not reveal the presence of any single (or series of) dominating hydrocarbon(s) (Fig. 5). A blue streak extending from the origin to the solvent front was apparent under long wavelength UV illumination. Chromatography of the PAH fraction from the sublittoral sediment samples generally revealed a continuous series of multicolored fluorescing bands under UV illumination and a series of peaks in the fluorescence scan (Fig. 5). The band that had an R_f value identical to benzo[*a*]pyrene had a fluorescence emission spectrum identical to the standard. Although differences in the relative intensities of peaks were observed, the same pattern was present in all samples.

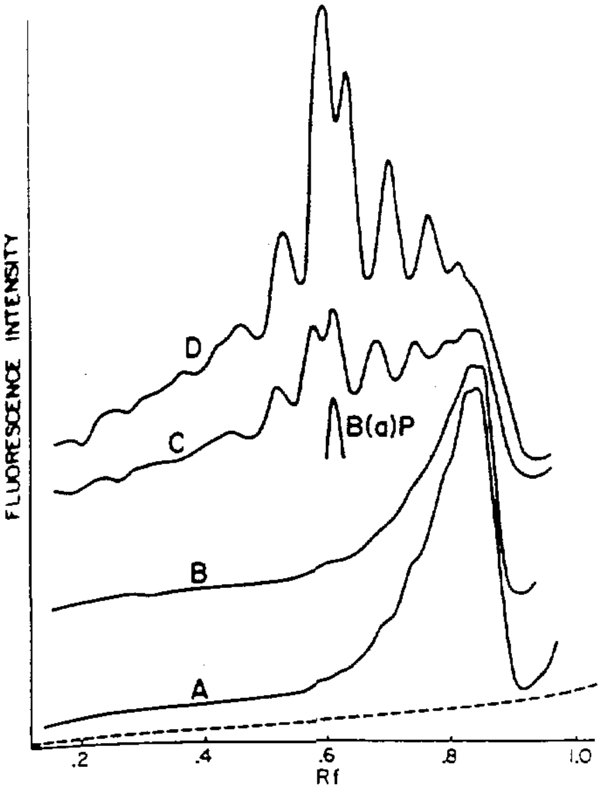

FIG. 5. Fluorescence emission scans of TLC plates of PAH fractions (reverse phase cellulose — 20% DMF in ether developed in isooctane). Excitation wavelength, 365 nm; emission wavelength, 445 nm. A *Arrow* Bunker C fuel oil; B weathered *Arrow* Bunker C fuel oil; C extract from sublittoral sediment containing petroleum residues; D extract from unpolluted sublittoral sediments.

This widespread uniformity in the composition of the PAH fraction of sediment extracts has been observed before (Youngblood and Blumer 1975) and suggests a common source, possibly the anthropogenic combustion of fossil fuels (Hites et al. 1977).

The presence of an underlying blue streak and/or a strong blue band near the solvent front is indicator of the presence of petroleum-derived hydrocarbons in samples. This visible feature was always correlated with small peaks superimposed on a high background in the fluorescence scans. The samples taken at the mouth of the Strait of Canso, near Eddy Point, and just north of Durell Island, had TLC scans identical to Bunker C fuel oil. Both these locations are probably the recipients of chronic pollution from ship traffic.

Gas–liquid chromatography — A chromatogram of the aliphatic fraction of a sample of *Arrow* Bunker C fuel oil is shown in Fig. 6. It is characterized by a series of *n*-alkanes and isoprenoids on an envelope due to a UCM of principally naphthenic hydrocarbons (Blumer et al. 1970). Numerous studies (e.g. Atlas and Bartha 1973) have documented the rapid bacterial degradation of the *n*-alkanes, the UCM being much more resistant to degradation.

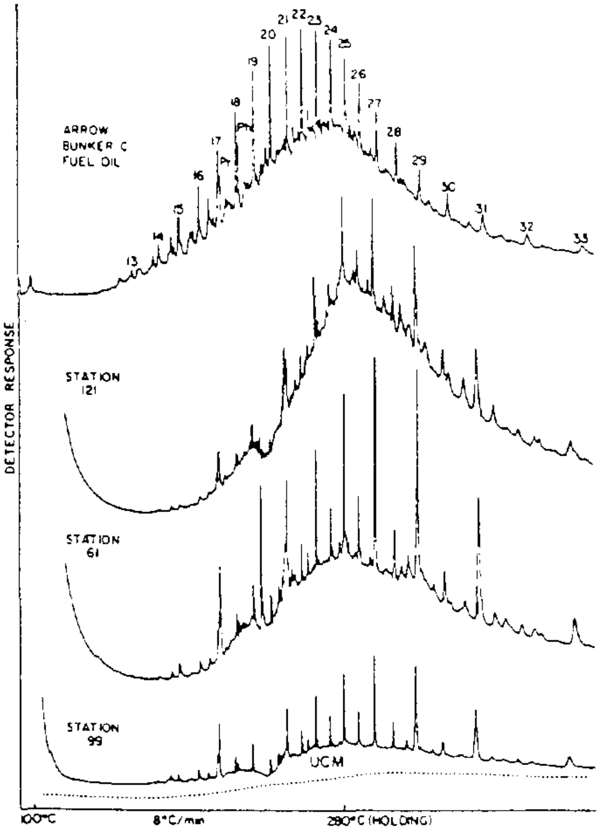

FIG. 6. Gas–liquid chromatograms of aliphatic fractions of *Arrow* Bunker C fuel oil and sediment extracts from Stations 121 (north of Janvrin Island), 61 (north of Durell Island), and 99 (45°25′N, 60°50′W) exhibiting, in order, decreasing degrees of petroleum hydrocarbon contamination. The broken line is the background signal; numbers above peaks indicate the number of carbons in the corresponding *n*-alkanes; Pr is pristane and Ph is phytane. Chromatograms represent approximately the same weight of sediment.

The aliphatic fraction from all of the sublittoral samples contained a series of *n*-alkanes that had a strong odd-carbon preference (Fig. 6) indicative of a biogenic terrestrial source for these hydrocarbons (Farrington and Meyers 1975). The sample from near the mouth of the Strait of Canso was an exception. It had a carbon preference index (Bray and Evans 1961) of 1.03 for nC_{16}–nC_{30} with a maximum concentration at nC_{23}, a strong signal for the UCM peaking at nC_{22}, and an nC_{18}/phytane ratio of 1.35. These are all strong indicators of recent petroleum hydrocarbon input (Farrington and Meyers 1975).

Chromatograms of the aliphatic fraction of all samples had a measurable unresolved envelope. The concentration of this UCM ranged from barely detectable,

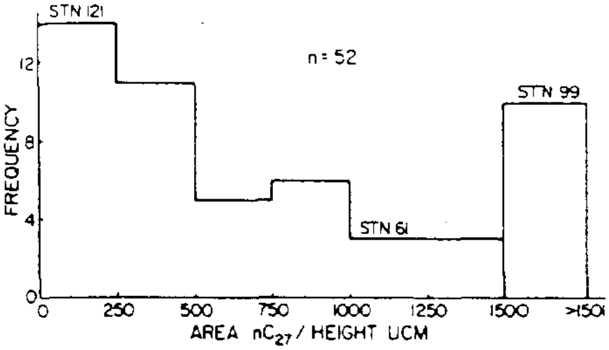

FIG. 7. Frequency distribution of the ratio of the nC_{27} peak area to the height of the UCM at nC_{27}. The class to which the chromatograms from Fig. 6 belong is indicated. The probability of oil residues in the samples increases from right to left.

<0.05. to 117 μg/g dry sediment. The shape of the UCM was generally different than that for *Arrow* Bunker C and indicated the loss of some of the lower boiling components (Fig. 6). Most crude and residual fuel oils contain a UCM and the presence of a UCM in marine organism extracts is generally taken as an indicator of the presence of petroleum hydrocarbons (Farrington and Meyers 1975). Farrington and Tripp (1978) have reviewed the possible sources of the UCM in marine sediments and have concluded that the presence of the UCM is a strong indicator of fossil hydrocarbon contamination.

Extracts from these sediments had UCM's that varied considerably in shape and intensity (Fig. 6). A measure of the relative intensity of the UCM was made by comparing the area of the nC_{27} peak relative to the height of the UCM at this point. The frequency distribution of this data is plotted in Fig. 7. Samples that have ratios in the far left of the histogram have a larger UCM relative to the concentration of *n*-alkanes and therefore a higher probability of containing petroleum-derived hydrocarbons than those on the far right. The class to which the chromatograms from Fig. 6 belong is indicated.

Based on the nC_{27} to UCM ratio and the fluorescence TLC scans of the PAH fraction, probabilities were assigned for the presence of petroleum-derived hydrocarbons in a sample. On this basis petroleum-hydrocarbon residues in sublittoral sediment extracts are found principally in heavily traveled areas (Fig. 3) where the source of the residues is complicated by inputs from many sources over long periods of time. On the northern shore, stations with sediment extracts containing petroleum residues are concentrated near the entrance to the Strait of Canso and Cerberus Rock. This may be the result of either a large proportion of the fuel oil spilled from the *Arrow* being swept there by natural forces and/or chronic spills by ships using the Strait of Canso. It is impossible to say whether or not the petroleum residues in the sediment came from the *Arrow*; however, the residues appear to be extensively weathered. The *n*-alkanes have disappeared and the composition of the PAH fraction is significantly different from that of a petroleum product.

Oil may reach the sublittoral sediments by a number of pathways. For a residual fuel oil such as Bunker C the loss of volatile and soluble components and the detachment of mineral particles can result in an oil residue with a density greater than that of seawater (McAuliffe 1977). In the case of the *Arrow* spill, the density of the surface waters was only 5% greater than that of the spilled oil (Conover 1971). Conover (1971) concluded that zooplankton were responsible for the removal of oil droplets from the water column by ingestion and subsequent sedimentation as oil incorporated with other fecal material. In addition to these methods of sedimentation, stranded oil that has been mixed with intertidal sediments is swept into the water column by wave and tidal action and finds its way to the sublittoral sediments. The distribution of oil-containing sediments and the absence of a petroleum-derived *n*-alkane series favors the last pathway as the major source of petroleum-derived hydrocarbons in the surficial sublittoral sediments of Chedabucto Bay. If it were assumed that all of the extractable organic material from these sediments were *Arrow* Bunker C, the concentrations would still be far below the level at which toxicity to benthic organisms is observed (e.g. Gordon et al. 1978).

Conclusions

Stranded oil from the tanker *Arrow* has disappeared from most of the shoreline of Chedabucto Bay, 6 yr after the spill. Visual observations and chemical analyses of samples from 600 km of shoreline (including 260 stations) revealed the presence of petroleum hydrocarbons at most locations. However, due to weathering and contamination from recent spills, identification of the residues as *Arrow* Bunker C is impossible.

Only a few isolated spots remain that are visibly contaminated with large quantities of oil identifiable as *Arrow* Bunker C. These are Rabbit, Crichton, and Durell islands, where the upper high tide zones remain covered with a mixture of oil and sediment in a "pavement-like" consistency.

Estimation of the amount of oil buried within the intertidal sediments is hampered by its patchy distribution and re-oiling and contamination from other sources. Chemical analysis of the aliphatic and polycyclic aromatic hydrocarbon fractions of sediment extracts from one location studied in detail (Moussilier Passage) indicated recent contamination with a light fuel oil. In several other areas there was visual evidence of light-fuel-oil spills during the survey period.

Chemical analysis of the aliphatic and polycyclic aromatic hydrocarbon fractions of 72 of the 137 sublittoral samples collected indicated a variable degree of contribution of petroleum hydrocarbons to the extractable organic material. The samples that contained the highest concentrations were generally located along the northern shore and in the Strait of Canso area. It is not possible to determine whether *Arrow* Bunker C is the source of these hydrocarbons because of extensive weathering and probable input from recent spills. However, the distribution suggests that the source may be the reentry of stranded oil into the water column and into the sublittoral sediments near the shore.

The main difficulty in a study of this type is our inability to find a control site that has not been contaminated by petroleum hydrocarbons and does not have measurable quantities of petroleum-derived hydrocarbons in its intertidal and sublittoral sediments. Without an appreciation for what "background" levels might be, it is impossible to assess the magnitude of petroleum-hydrocarbon input from a spill.

Acknowledgments

We thank Mr W. R. Hardstaff, Ms L. Rutley, and the captain and crew of the *Whip-the-Wind* for their assistance in conducting the survey and Dr D. C. Gordon, Jr. for his many helpful suggestions. The Canadian Coast Guard provided helicopter time for preliminary aerial reconnaissance of the study area.

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Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia

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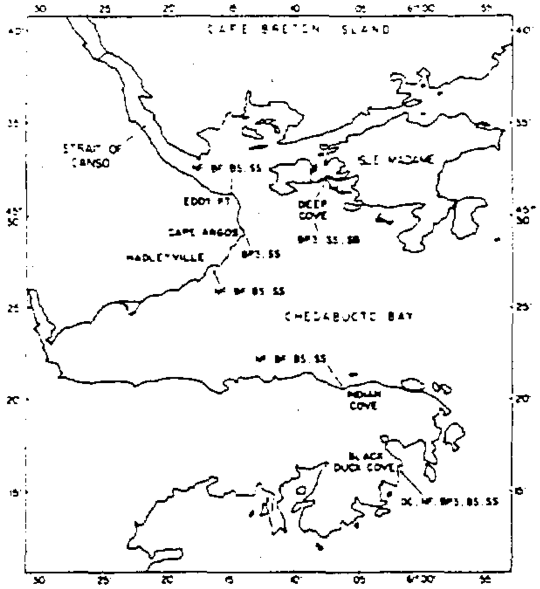

FIG. 2. Location of study sites in Chedabucto Bay. BP—beach profiles 1970 to 1973; BP3—beach profiles 1973; BS—nearshore bottom samples; NP—nearshore profiles; OC—oil cover study; SB—sediment budget study; SS—beach sediment size estimates.

graphical distribution of oil in the shore zone, and (3) the impact of littoral processes on the physico-chemical properties of oil residues on the shoreline.

To establish the effects of sediment removal from the littoral zone, data were obtained in 1973 from nearshore bottom profiles, bottom samples, and resurveys of beach profiles studied in 1970 (Owens and Drapeau 1973) at Eddy Point, Hadleyville, and Indian Cove (Fig. 2). On a larger scale, an aerial reconnaissance of the coast was repeated to record changes in the oil cover on the shoreline over a 3-year period and to obtain comparative photography of specific localities. A study of the coastal environment at Black Duck Cove, on the Atlantic coast adjacent to Chedabucto Bay, was concerned with the natural physical and chemical degradation of oil in the littoral zone. In addition, a sediment budget study was undertaken at Deep Cove to provide an estimate of the rate of supply of material to the littoral zone from the erosion of till cliffs.

The natural environment has been altered directly or indirectly by man at each of the study sites in Chedabucto Bay. The results of the different studies discussed below provide specific data which can be used for better management of the coastal zone and in planning for handling future oil spills.

Coastal Environments and Shore Zone Dynamics

The character of the shore zone of Chedabucto Bay ranges from sheltered, low-energy beaches composed of poorly sorted till-derived sediments, cobble and boulder beaches, to resistant rock cliffs directly exposed to the Atlantic Ocean. The combination of the inherited factors, such as bedrock, surficial sediments, and relief, with the dynamic features of terrestrial and marine processes gives this area a great variety of coastal environments. Owens (1971*a*) presented a map of shoreline types that illustrates the geographic distribution of geomorphic features on the basis of a reconnaissance study, and discussed the dynamic and inherited features of the coastal zone. Although the map demonstrates the local variation and complexity of the coast, it is possible to distinguish four major coastal environments: the North Coast, the West Coast, the South Coast, and the Atlantic Coast.

The recent rise in sea-level, at a rate of about 15 cm/century in this area (Grant 1970), has produced a drowned shoreline, and the primary subdivision of the coast is based upon the geologic regions defined by the Chedabucto Bay fault zone. North of this fault, a series of Carboniferous sedimentary rocks have been modified by glacial and fluvial erosion into an undulating lowland region (Grant 1971, 1974). South of the fault zone, resistant metamorphic and intrusive lower Palaeozoic rocks have been uplifted and eroded to form an upland plateau which dips towards the south. The distribution of surficial sediments closely reflects these two geologic regions with relatively thick deposits of red, loam tills to the north of the fault and a discontinuous cover of stoney tills to the south (Owens 1971*a*, fig. 3).

Subdivision of these two primary units is based on more local variation in shoreline orientation, relief, and exposure to wave energy. East of the Strait of Canso, the north shore of Chedabucto Bay consists of a complex series of islands, inlets, and bays that results from the submergence of the Carboniferous lowlands. Areas sheltered from direct wave approach have low-energy beach environments, usually characterized by a

Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia

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Investigations following the oil spill from the tanker ARROW in Chedabucto Bay, Nova Scotia, in 1970 have focussed on the physical and chemical degradation of the Bunker C oil in different littoral environments and on the effects of sediment removal to restore polluted beaches. Natural processes have restored the beaches effectively on coasts exposed to wave activity. In sheltered, low-energy areas, the oil has undergone relatively little change over the 3-year period and is still present in the littoral zone. The removal of contaminated sediments from exposed beaches has not caused major changes but has resulted in permanent retreat of the beach crest in areas of limited sediment supply.

A la suite des pertes d'huile du pétrolier ARROW dans la baie de Chedabucto, Nouvelle-Ecosse, en 1970, des recherches ont été consacrées à la dégradation physique et chimique de l'huile Bunker C dans différents environnements littoraux, et aux effets de l'enlèvement de sédiments effectué en vue de restaurer les plages polluées. Les processus naturels ont restauré les plages de façon effective sur les côtes exposées à l'activité des vagues. Dans les régions abritées, de basse énergie, l'huile a subi relativement peu de changements sur la période de 3 ans écoulée et est toujours présente dans la zone littorale. L'enlèvement des sédiments contaminés n'a pas provoqué de changements majeurs sur les plages exposées, mais, dans les régions où l'apport de sédiments est limité, il en est résulté un retrait permanent de la crête de plage.

[Traduit par le journal]

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Introduction

A reconnaissance of the coastal zone characteristics of Chedabucto Bay (Fig. 1) was undertaken in spring, 1970. This study formed part of a scientific program initiated by a Ministry of Transport Task Force established following the spill of 4.8 million gallons (21.8 ml) of Bunker C oil from the tanker ARROW (Canada Ministry of Transport 1970). The reconnaissance provided a rapid assessment of coastal geomorphology, littoral processes, and beach sediments that was used as the basis for developing a beach-cleaning program. In areas where the restoration of beaches involved sediment removal, repetitive surveys were carried out to determine the immediate effects on beach stability (Owens and Drapeau 1973). Subsequent investigations result from an integrated multidisciplinary research program on the environmental marine geology of the Canso Strait – Chedabucto Bay region, undertaken in 1973 by the Atlantic Geoscience Centre of the Geological Survey of Canada (Buckley *et al.* 1974; Vilks *et al.* 1975).

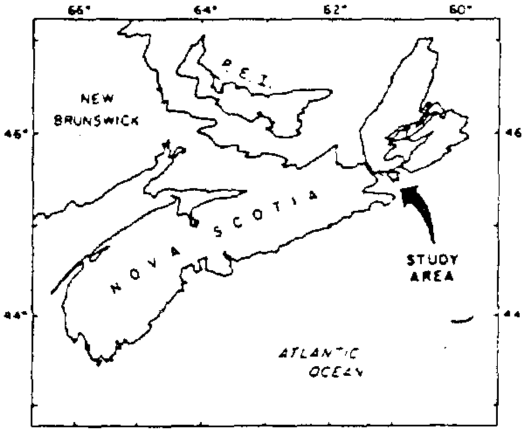

FIG. 1. Location of Chedabucto Bay, Nova Scotia.

The objectives of this paper are to report on the impact of man in Chedabucto Bay with reference to (1) the effects of beach restoration in the polluted areas, (2) changes in the geo-

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thin (30–40 cm) layer of poorly sorted mud, sand, and pebbles resting on a till platform. By contrast, on the exposed coasts, intensive wave action has resulted in shoreline simplification by the erosion of headlands and by deposition across embayments.

The second unit, to the west of the Strait of Canso, is also within the Carboniferous lowlands, but differs from the north coast on the basis of the more regular topography that gives a relatively straight coastal configuration. Submergence of this southeast-sloping lowland area has produced a series of broad drowned valleys separated by eroding till or bedrock headlands. During the post-glacial transgression, the easily eroded tills, conglomerates, sandstones, and shales supplied large volumes of sediment to the littoral zone that have been reworked to build large barrier features across the re-entrants. This coast is open to direct wave action from the east and the beaches are characterized by a wide, often steep, intertidal zone with large cobble storm-ridges.

The south coast of Chedabucto Bay forms a straight faultline-scarp shoreline (Johnson 1925). The coast is characterized by low, resistant rock cliffs and intertidal platforms, with occasional pocket beaches where sediments have accumulated in bays produced by erosion along secondary faults or joint planes.

To the east and south of Fox Island, the fourth unit (the Atlantic Coast) is a complex region of drowned, irregular, resistant, lowland topography exposed to constant attack by storm and swell waves. Sediments are scarce due to the lack of glacial deposits and the resistant nature of the rock outcrops.

These different coastal environments will be discussed in the context of data collected during specific studies at five locations. The studies provide an account of some of the effects of man in the coastal zone at Chedabucto Bay through (1) an analysis of till cliff erosion rates and an estimation of the sediment budget at Deep Cove (North Coast); (2) measurement of the effects of sediment removal on beach profiles at Eddy Point (West Coast), Hadleyville (West Coast), and Indian Cove (South Coast); and (3) the investigation of oil in the littoral zones of Black Duck Cove (Atlantic Coast).

Deep Cove

The northern coast of Chedabucto Bay has a complex shoreline as a result of drowning of the irregular and glaciated lowland terrain. In sheltered wave environments, rates of erosion are very low and depositional processes are slow so that the shoreline has only partially adjusted to littoral processes. Along the exposed sections of this coast, shoreline erosion of the red loamy till cliffs has been rapid, and this has resulted in the development of wide, shallow, wave-cut platforms that now partially absorb the energy of incoming waves. However, erosional and depositional processes are still important, particularly during periods of storm waves. Between Janvrin Island and West Arichat, a series of islands have been connected by deposition of bars across the shallow embayments to give a relatively straight coastline of alternating narrow bars and eroding till cliffs (Fig. 3).

Estimates of the volumes of sediment that are being supplied to the littoral zone of this coast result from a study of till erosion on a 5.1 km section of shoreline in the Deep Cove area. Shoreline changes and rates of cliff erosion were measured from vertical aerial photographs taken in 1936, 1953, and 1973 (Fig. 3). Rates of cliff erosion vary considerably in this area, ranging from less than 10 cm/y to a maximum of 135 cm/y. The bars that connect the till cliffs are retreating at rates between 14 and 162 cm/y. In addition, 21 profiles were surveyed across the shore zone in 1973 (Fig. 3) so that the total volume of material eroded or deposited during the 37-year period could be calculated. The till cliffs are rarely more than 10 m in height and are composed of red clay-loam or gravelly clay-loam sediments. Textural analysis of six sediment samples (numbers 5601 to 5606, Table 1) from till cliffs indicate that the size characteristics of the samples from this coast and two samples (5607 and 5608) from the west coast near Cape Argos (Fig. 2) are remarkably uniform. The per cent of each size fraction per cubic metre of till was calculated (Table 2), allowing an estimate of the annual supply of each size fraction (Table 3).

The beaches of this section of shoreline are composed largely of material in the granule–pebble–cobble size fractions, which have an annual rate of supply in the order of 2000 m^3/y. Boulders are rarely moved by wave action and accumulate *in situ* at the base of the till cliffs, whereas the silt and clay fractions are removed in suspension, and the sand fraction is transported into the nearshore areas.

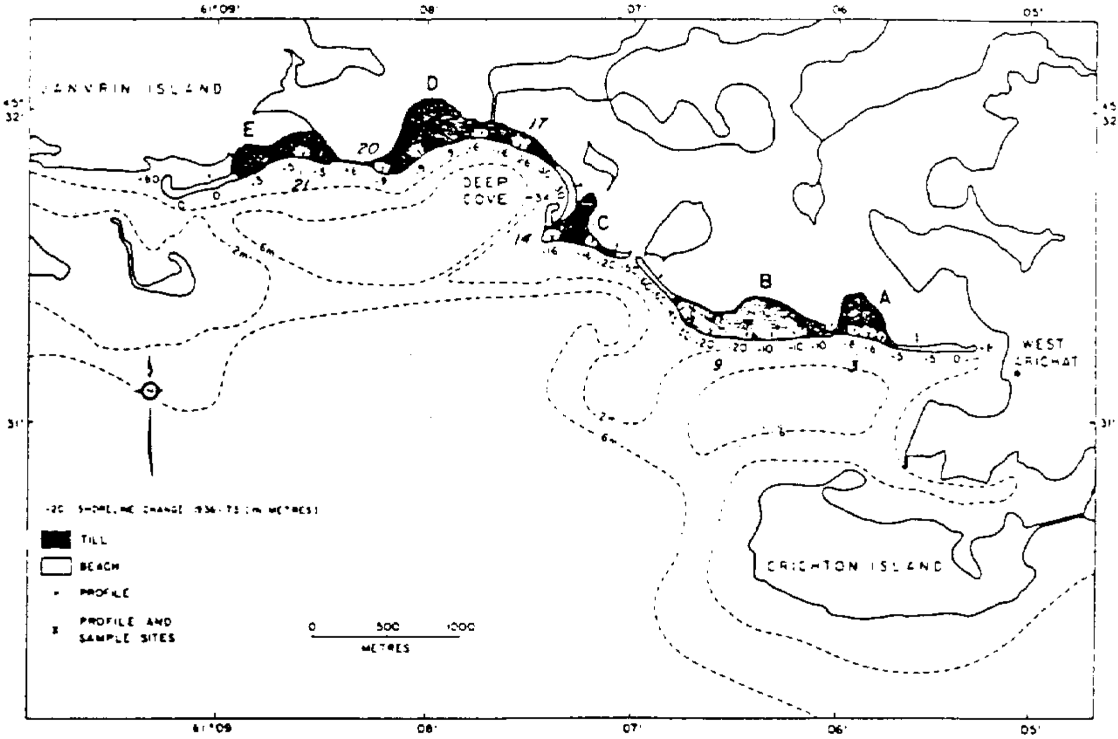


FIG. 3. Deep Cove study area, shoreline changes (1936–1973), profile locations and sample sites. The letters A to E refer to the five till cliff units (Table 3).

TABLE 1. Size analysis of till cliff samples (DC = Deep Cove: CA = Cape Argos). The location of the Deep Cove samples is shown on Fig. 3

Sample No.	Profile	Boulders (per m³)	Cobbles (per m³)	Pebbles wt%	Granules wt%	Sand wt%	Silt, clay wt%
5601	DC 3	7	55	33.2	5.7	15.2	45.9
5602	DC 9	6	55	18.1	5.2	18.2	58.5
5603	DC 14	6	45	15.4	4.3	17.1	63.2
5604	DC 17	3	50	16.4	5.0	17.4	61.2
5605	DC 20	3	40	11.7	4.7	16.3	67.3
5606	DC 21	6	50	19.6	5.7	15.6	59.1
MEAN		5	50	19.0	5.1	16.6	59.1
5607	CA 1	2	80	16.8	4.8	18.2	60.2
5608	CA 2	5	60	17.0	4.1	21.6	57.3

Each year, erosion of the till cliffs supplies sufficient material in the granule-pebble–cobble size range to deposit a layer of sediment 10 m wide and 12 cm deep in the littoral zone of the beaches directly adjacent to the cliffs. If more than 2000 m³ of sediment is removed per year from beaches in this area, shoreline stability will be markedly affected. Beach sediment is commonly removed for construction purposes in this region and has been observed in this study area since 1970. The retreat of the bars which connect the islands must be in part, if not solely, due to sediment removal by man. Under natural conditions, there is sufficient material supplied to the littoral zone to maintain, and in some cases build up, the beaches. The beaches that have suffered retreat along this section of coast are those where there is direct evidence of recent

TABLE 2. Volumetric analysis of till cliff samples at Deep Cove

Boulder	Cobble	Pebble	Granule	Sand	Silt, clay	Water
6.5%	6.2%	12.8%	3.4%	15.9%	37.3%	17.9%

TABLE 3. Estimates of annual sediment supply rates at Deep Cove. Sections of till exposed on the shoreline are outlined in Fig. 3

Section	Length (m)	Maximum height (m)	Maximum erosion rate (cm/y)	Volume of size fractions supplied by erosion (m^3/y)						
				Boulders	Cobbles	Pebbles	Granules	Sand	Silt, clay	Total
A	320	6.3	25	20.8	19.8	41.0	11.0	51.0	119.4	263.0
B	1168	13.0	135	348.9	332.8	688.4	184.7	856.3	2004.0	4415.1
C	230	6.7	45	22.4	21.4	44.2	11.9	55.0	128.7	283.6
D	1144	11.7	73	199.5	190.3	393.5	105.6	489.5	1145.6	2524.0
E	540	11.1	14	19.4	18.5	38.2	10.2	47.5	111.2	245.0
TOTAL	3402			611.0	582.8	1205.3	323.4	1499.3	3508.9	7730.7

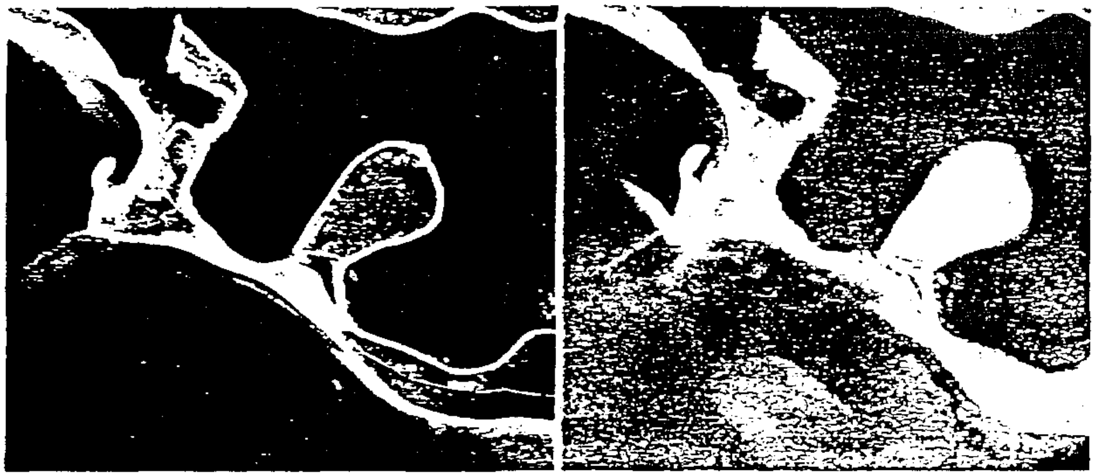


FIG. 4. Comparison of 1953 (left) and 1973 (right) vertical air photographs of the Deep Cove area. Although the 1953 photograph was taken at a time of higher tide level than the 1973 photograph, the shoreline changes in the central part of the photographs are evident. (National Air Photo Library, Ottawa, Canada: (a) A13718-42, 1953, 1:17 000, (b) RSA23312-116, 1973, 1:17 000).

sediment removal; where sediment has not been removed by man, there has been net sediment accumulation. The effect of sediment removal during the last 20 years is particularly evident between sections B and C (Fig. 3), where the narrow bar has eroded 40 to 50 m since 1953 (Fig. 4); whereas in the period between 1936 and 1953, the beach was eroded only 10 to 12 m. The retreat of this beach has in turn resulted in an increase in the rate of erosion of the adjacent till cliffs (Owens 1971*a*, photo 11). The beaches of this area are in a delicate equilibrium with the littoral processes and with the sediment supply, so that the impact of man in disturbing the natural system can have immediate and adverse effects on the shore zone.

Hadleyville

Along the western margin of Chedabucto Bay, glacial deposits, exposed on the coast as cliffs that vary in height from 3 to 30 m, overlie unresistant Horton Group (Mississippian) red

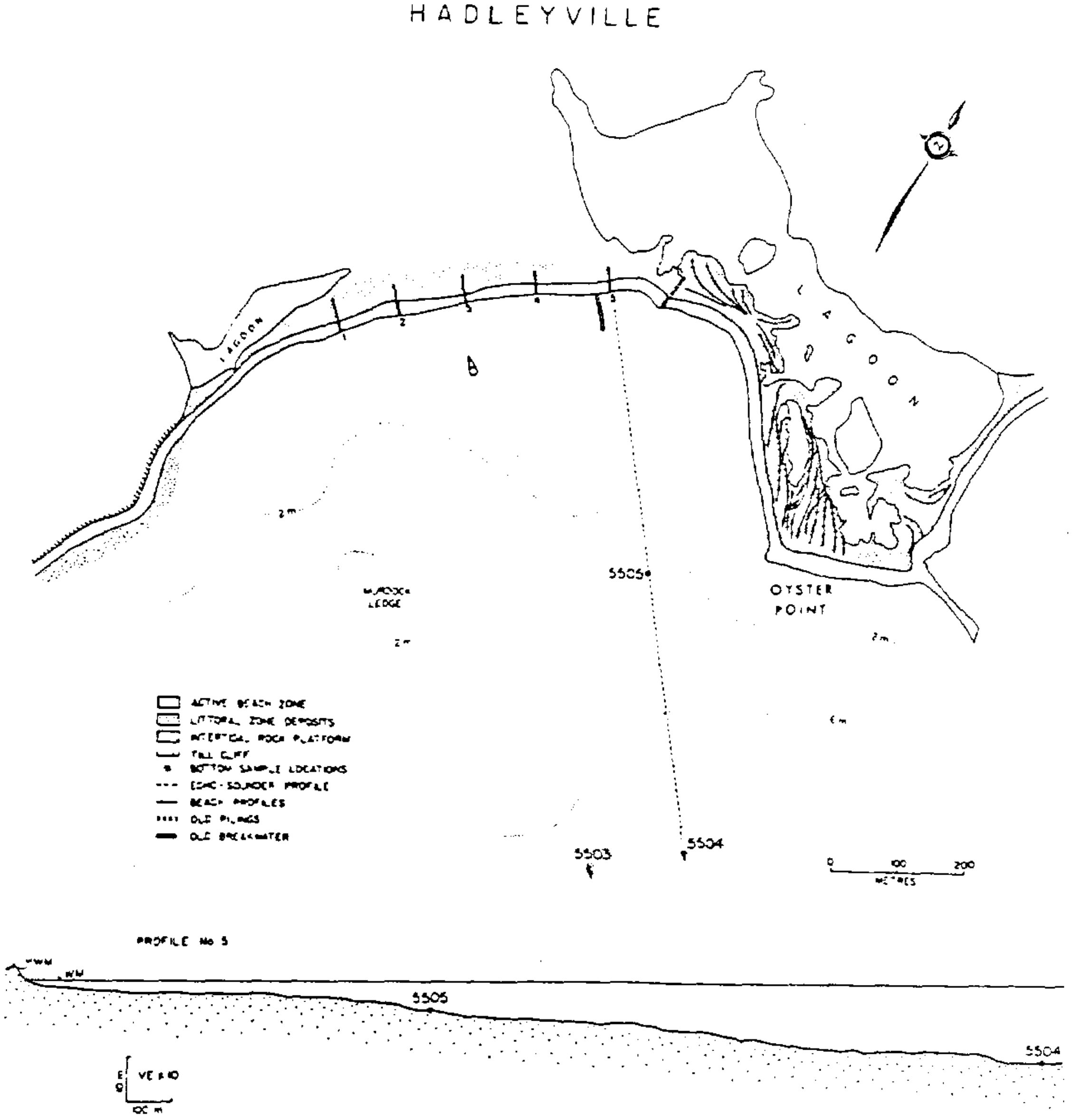


FIG. 5. Hadleyville study area, with beach–nearshore profile on line 5.

sandstones and shales. The glacial deposits are mainly red clay loam or gravelly-clay loam tills (Hilchey *et al.* 1964) that are composed largely of silt–clay size sediments (Table 1; samples 5607 and 5608). The coast is undergoing rapid modification by deposition across the shallow embayments and by erosion of the unresistant cliffs. The littoral zone sediments are mainly in the sand–pebble–cobble range, and these are derived from contemporary erosion and from the products of erosion that have accumulated by the landward migration of beach ridges during the post-glacial transgression.

The beach at Hadleyville (Fig. 5) is characteristic of many of the depositional features on the western shore of Chedabucto Bay. The beach face is wide, up to 40 m at low tide, and has a high storm ridge, up to 4 m above mean low water level. Typically the size of material grades from medium sand in the intertidal zone, to

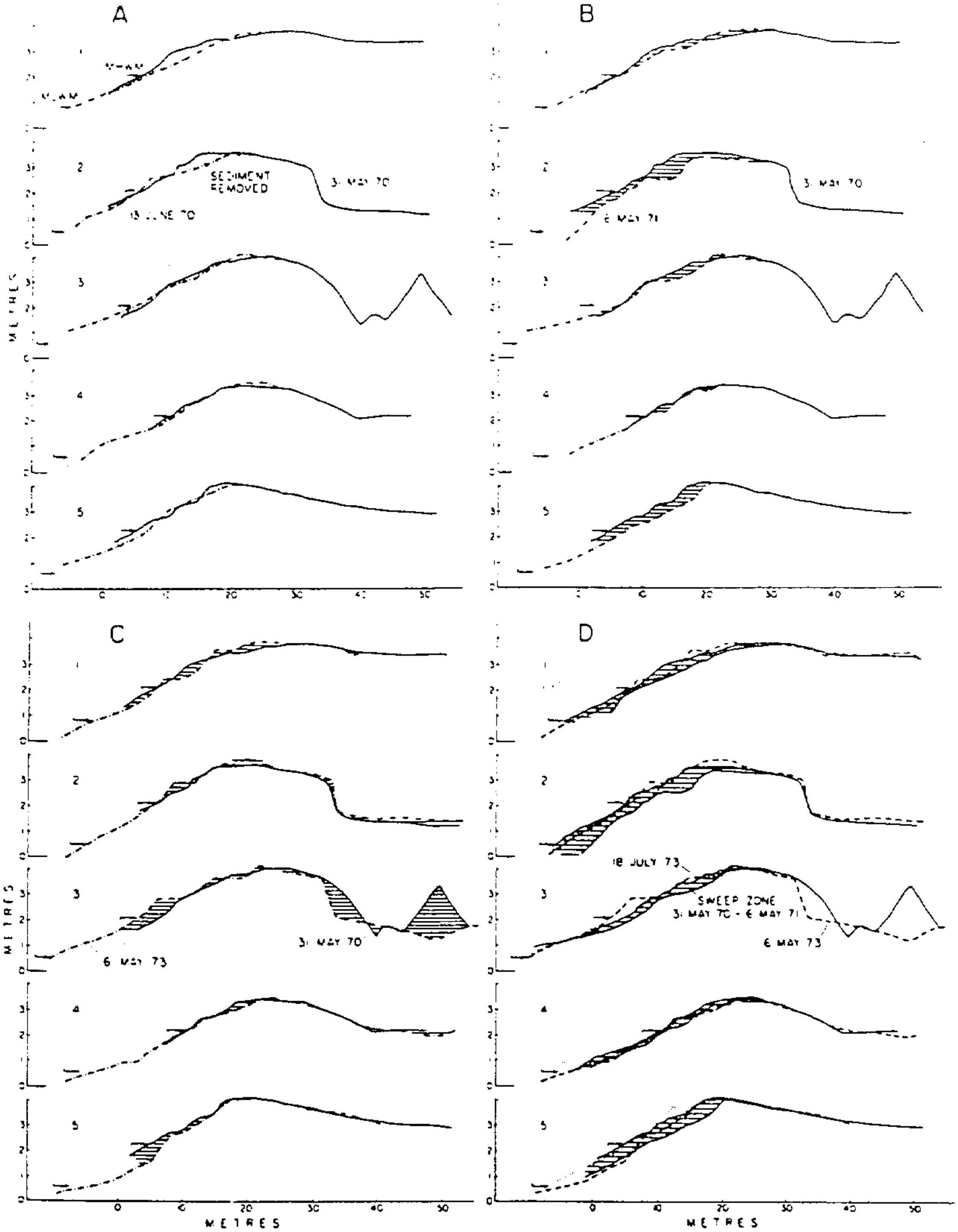
TABLE 4. Textural characteristics of nearshore bottom samples. Locations of samples are indicated on the profile lines for each study area (n/s—no sample).

Sample number	Location	Depth (m)	Distance from beach (m)	Pebbles wt%	Granules wt%	Sand wt%	Silt, clay wt%
5501	Eddy Point	34	1020	0.2	0.3	16.4	83.1
5502	Eddy Point	11.5	290	rock: n/s			
5503	Hadleyville	13	2130	cobbles/pebbles			
5504	Hadleyville	17	2240	rock/cobbles			
5505	Hadleyville	6	880	rock: n/s			
5506	Indian Cove	20	1340	rock: n/s			
5507	Indian Cove	14	660	0.2	0.1	59.0	40.7
5508	Indian Cove	11	460	0.7	0.2	85.2	13.9
5509	Indian Cove	8	290	10.6	4.1	83.5	1.8
5510	Indian Cove	5	110	0.4	0.8	94.7	4.1
5511	Black Duck Cove	16	810	0.1	0.1	44.5	56.3
5512	Black Duck Cove	14	650	0.1	0.2	73.8	25.9
5513	Black Duck Cove	9	415	0.0	0.1	84.9	15.0
5514	Black Duck Cove	6	200	0.0	0.0	98.0	2.0
5515	Black Duck Cove	2	channel	0.0	0.1	98.1	1.8
5516	Black Duck Cove	3.5	channel	boulders/cobbles: n/s			

pebbles near mean high water mark, and cobbles on the beach crest (Owens 1971*a*, table 4). Sediment transport in the littoral zone is from west to east on this beach, and the depositional foreland of Oyster Point at the eastern limit of this beach (Fig. 5) appears to result from the convergence of wave-induced longshore drift. Offshore gradients are low, and bottom samples (Table 4) indicate a rock or till surface covered with pebble- to cobble-sized material. The bottom profiles indicate a marked break of slope at about 5 m depth (Fig. 5) and this may be due either to bedrock control or to wave erosion at a time of relative sea-level stability. Murdock Ledge is the submerged remnant of an island that was used as pasture during the late nineteenth century and which was connected to the land by a road.

During the spring of 1970, the beach at Hadleyville was contaminated by oil from the grounded tanker ARROW. Most of the oil was deposited at or near the beach crest during periods of storm wave activity. On the pebble or cobble sediments, oil permeated down to a depth of 45 cm (Drapeau 1970; Owens 1973) and reworking of the sediments by waves led to the burial of some contaminated material, which was subsequently exposed as layers in the beach-face slope. The clean-up program directed by the Task Force resulted in the removal of approximately 3000 m^3 of material from a 1400 m section of this beach (Owens 1971*b*). The depth of sediment removal varied considerably and in certain areas, where oil had been buried, up to 1 m was excavated (Fig. 6A). Most of the sediment was removed from the area above the intertidal zone because little oil was laid down in the zone of breaking waves and any oil deposited on the beach face was abraded easily by the mobile sediments. Owens and Drapeau (1973) discussed the beach profile changes for the 12-month period following sediment removal and noted that, although the beach was not seriously affected by the clean-up operation, the material excavated from the beach crest was not replaced by wave action during that period (Fig. 6B). Profiles surveyed on 6 May 1973 (Fig. 6C) show that material had been deposited in the supratidal zone during the preceding 24 months by storm wave action. This section of coast does not have a deficiency of sediments; therefore, the material that was removed from the active beach zone in

FIG. 6. Hadleyville beach profiles, 1970 to 1973. Profiles are located on Fig. 5. A. 31 May 1970 and 13 June 1970: before and after sediment removal. B. 31 May 1970 and 6 May 1971. C. 31 May 1970 and 6 May 1973. D. 31 May 1970 – 6 May 1971 'sweep zone' (cross hatched) with 6 May 1973 and 18 July 1973 profiles. (Vertical exaggeration × 4).



HADLEYVILLE

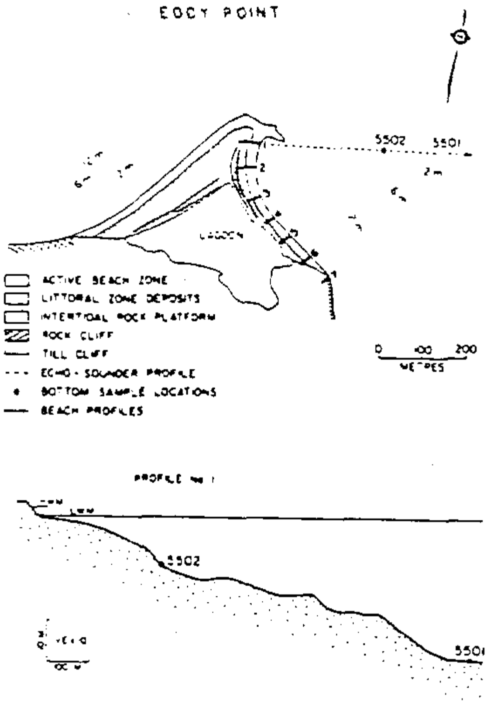


FIG. 7. Eddy Point study area, with beach–nearshore profile on line 1.

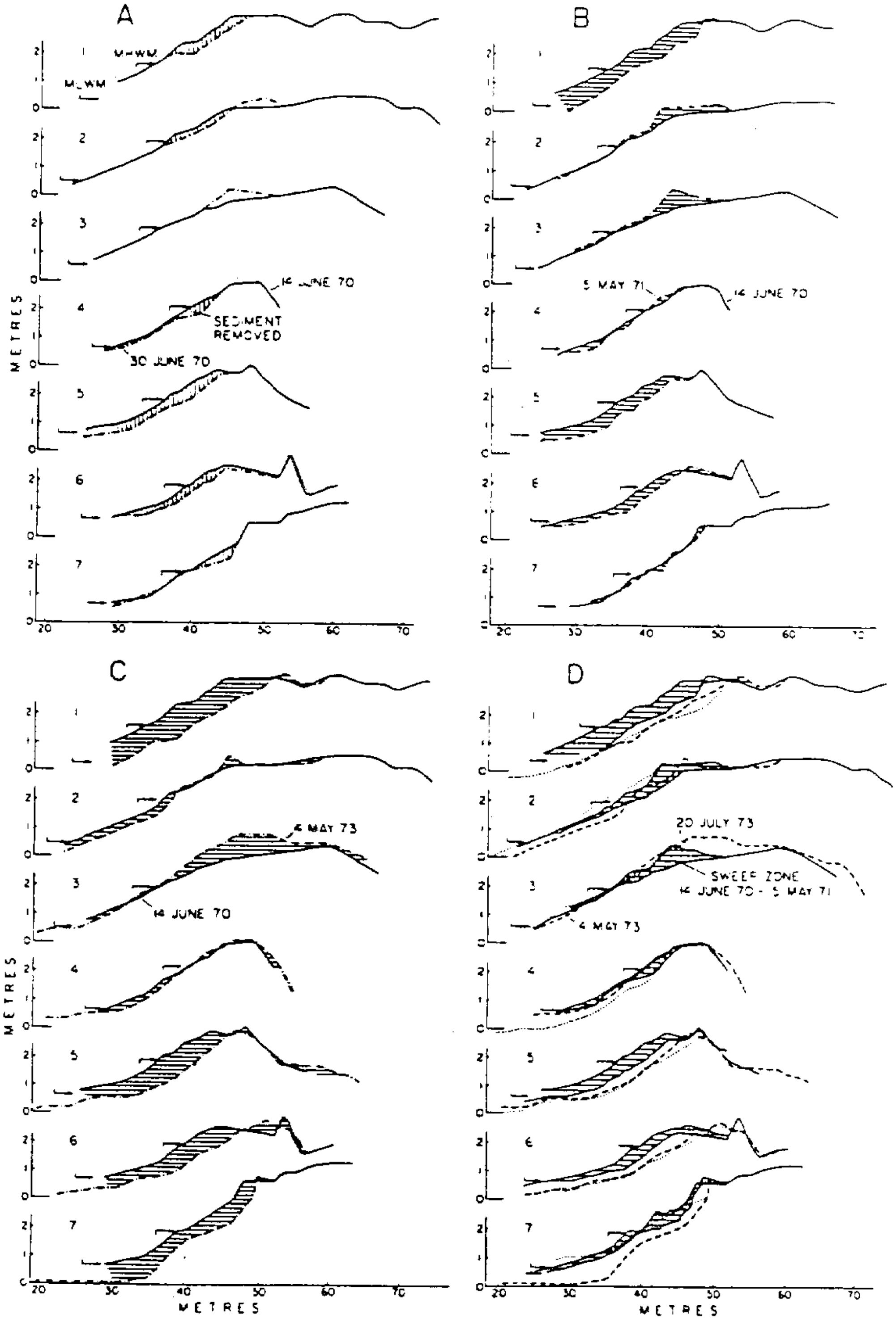
1970 had been replaced by normal littoral process. Figure 6D displays the five sets of beach profiles measured between May 1970 and May 1971 as a "sweep zone" (King and Barnes 1964), and it is apparent that the two sets of profiles surveyed in 1973 fall within the range of earlier observations. Although some parts of each profile may extend above or below the sweep zone, these differences are considered within the range of normal variation, and it is concluded that the beach has not been altered by sediment removal.

Eddy Point

The barrier foreland at Eddy Point (Fig. 7 and Owens 1971*a*, photo 7) has developed on a shallow rock platform. There is a marked change in shoreline orientation at this location, and deposition has taken place as a result of longshore drift from the west and the south. The foreland is slowly migrating to the west under the influence of waves from the southeast quadrant. The exposed east-facing barrier has a wide low-tide terrace, a steep beachface slope, and a storm ridge. The west-facing barrier is a low prograding beach in a more sheltered environment, with no storm ridge. The beach sediments are mainly in the pebble–cobble size range and offshore, these sediments rest on a rock or boulder platform. In deeper water the coarse sediments are replaced by silts and clays (Table 4, Fig. 7).

Oil spilt from the tanker ARROW contaminated this beach at various times during the spring of 1970. On the west-facing beach, oil was deposited as a continuous layer on the upper part of the intertidal zone. The contaminated material was removed mechanically and replaced by rock fill in order to minimize the effects of sediment removal on this low beach. Profiles surveyed across this beach showed no significant changes in the 5-month period following restoration (Owens 1971*b*). On the east-facing beach, which is subject to more intensive wave action, oil was deposited above the mean high water level and in some cases was buried due to the reworking of sediments. Removal of the contaminated material resulted in the beach being lowered by as much as 50 cm (Fig. 8A, profiles 1 and 5). During the 1-year period following excavation (Fig. 8B), the northern section of this beach suffered a net loss of sediment while the central section (profiles 2, 3, and 4) remained relatively stable. This pattern of change is still evident from profiles surveyed in 1973 (Fig. 8C and 8D), which show also that the beach at profiles 5 and 6 retreated in the order of 5 to 10 m over the 3-year period. This retreat may be a result of sediment starvation, as that material normally transported alongshore would be used to replace that lost by excavation. If this explanation is correct, then the normal process of transportation along the barrier has been interrupted and only the central section, which is the zone of sediment bypassing, has been unaffected. The barrier beach is very mobile and because of the large variations recorded in the beach profiles, it is not possible to distinguish with any degree of certainty those changes that were normal from those that resulted from sediment removal by man.

FIG. 8. Eddy Point beach profiles, 1970 to 1973, located on Fig. 7. A. 14 June 1970 and 30 June 1970: before and after sediment removal. B. 14 June 1970 and 5 May 1971. C. 14 June 1970 and 4 May 1973. D. 14 June 1970 – 5 May 1971 'sweep zone' (cross hatched), with 4 May 1973 and 20 July 1973 profiles. (Vertical exaggeration × 4).


A
B
C
D
MHWM
MLWM
14 JUNE 70
SEDIMENT REMOVED
30 JUNE 70
5 MAY 71
4 MAY 73
20 JULY 73
SWEEP ZONE
14 JUNE 70 - 5 MAY 71
METRES
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EDDY POINT

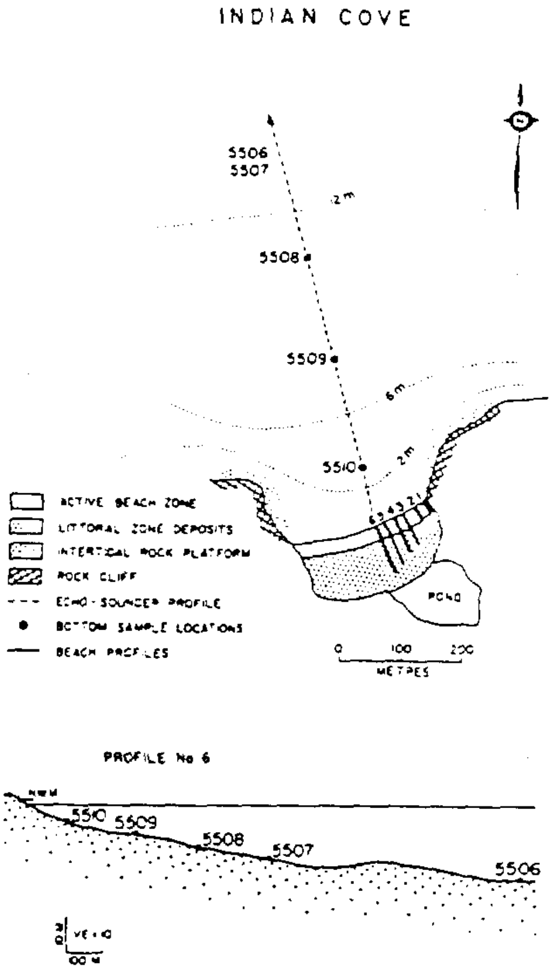


FIG. 9. Indian Cove study area, with beach–nearshore profile on line 6.

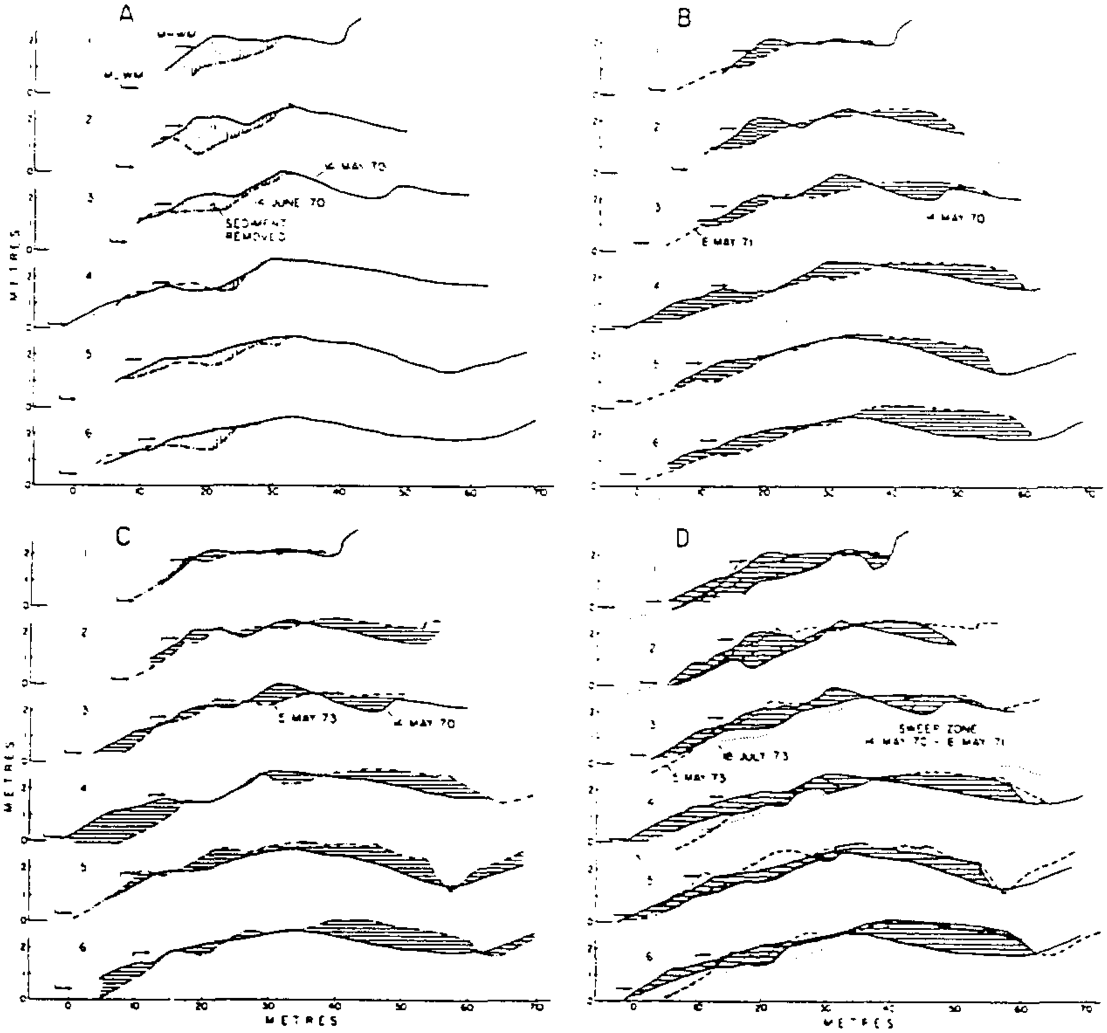
Indian Cove

The local configuration of the faultline-scarp shoreline of the south coast of Chedabucto Bay was developed by marine erosion along secondary faults and joint planes. The coast predominantly consists of rock cliffs and platforms with littoral sediments accumulating in sheltered locations. Indian Cove (Fig. 12 and Owens 1971*a*, photo 2) is an example of a pocket beach that was formed as a result of sediment build-up in a narrow bay formed by erosion along a northwest–southeast secondary fault. The beach at the head of the Cove is low, slowly prograding, and is sheltered from direct wave action out of the northeast. Sediments on the beach are predominantly in the pebble to coarse sand range, grading offshore to sand and muddy sand (Table 4, Fig. 9). Relatively little sediment is supplied to the littoral zone along this coast, due to the absence of till deposits along the shore zone, the resistant nature of the bedrock outcrops, and the steep offshore gradient. The shoreline at the entrance of the Cove is rock and is devoid of sediment. The only source for the littoral zone is material transported into the Cove on the sea-floor as bed-load or in suspension during periods of storm waves. Although the beach is prograding, as evidenced by abandoned ridges in the backshore, the rate of accumulation is slow because of the low volume of sediment input.

The beach was contaminated in 1970 by a thick (15 to 20 cm) and wide (3 m) layer of oil at the high water level. Attempts to clean the beach were initially unsuccessful, due to recontamination by oil released from rock pools on the adjacent shoreline. At the completion of the beach-cleaning program, up to 2 m of sediment were excavated from the eastern section of the beach (Fig. 10A). Little sediment was removed from the western section, and this part of the beach remained relatively unchanged throughout the period of observations. During the first 12-month period, the beach crest in the eastern section retreated between 10 and 20 m (Fig. 10B). As a result of sediment excavation, which lowered the level of the beach face, waves were able to wash over the crest and transport material into the low backshore area. Since 1971 it is evident that there has been a net loss of sediment in some sections (Fig. 10C and 10D, profiles 4 and 6; Owens and Drapeau 1973), but that the beach has established a new equilibrium position.

Black Duck Cove

The Atlantic shoreline of the Chedabucto Bay area is characterized by low, resistant rock cliffs and intertidal platforms with occasional pocket beaches and depositional features. The exposed sections of this drowned lowland coast are open to direct wave action from the east and southeast; these are high-energy wave environments. Investigations at Black Duck Cove (Figs. 2 and 11) provide information on the character of the littoral and nearshore zones and on the physical and chemical degradation of oil in the littoral zone. This section of coast is bounded by rock outcrops and part of the Cove has been closed



INDIAN COVE

FIG. 10. Indian Cove beach profiles, 1970 to 1973, located on Fig. 9. A. 14 May 1970 and 14 June 1970: before and after sediment removal. B. 14 May 1970 and 8 May 1971. C. 14 May 1970 and 5 May 1973. D. 14 May 1970 – 8 May 1971 'sweep zone' (cross hatched) with 5 May 1973 and 18 July 1973 profiles. (Vertical exaggeration × 4).

by a boulder spit to produce a shallow tidal lagoon. Within the Cove itself, which is set back from the main trend of the shoreline, a sandy pocket beach has developed.

The spit at Black Duck Cove has grown by transportation to the north of locally eroded material. Updrift of the spit, the littoral zone is characterized by a resistant rock platform, which is being eroded by storm and swell waves to produce large rectangular blocks up to 3 m on their longest axes. These angular resistant blocks are imbricated to the north, and are moved alongshore on the rock platform. The blocks become rounded and smaller in size (50–100 cm) through abrasion, and the spit is made up of well-rounded boulders that vary in diameter between 20 and 50 cm. In the sheltered lagoon, sediments are a poorly sorted mixture of silts, clays, sands, pebbles, and cobbles. The backshore (northwest) beach of the lagoon is predominantly pebbles and cobbles, which were at one time subject to direct wave action. Seaward

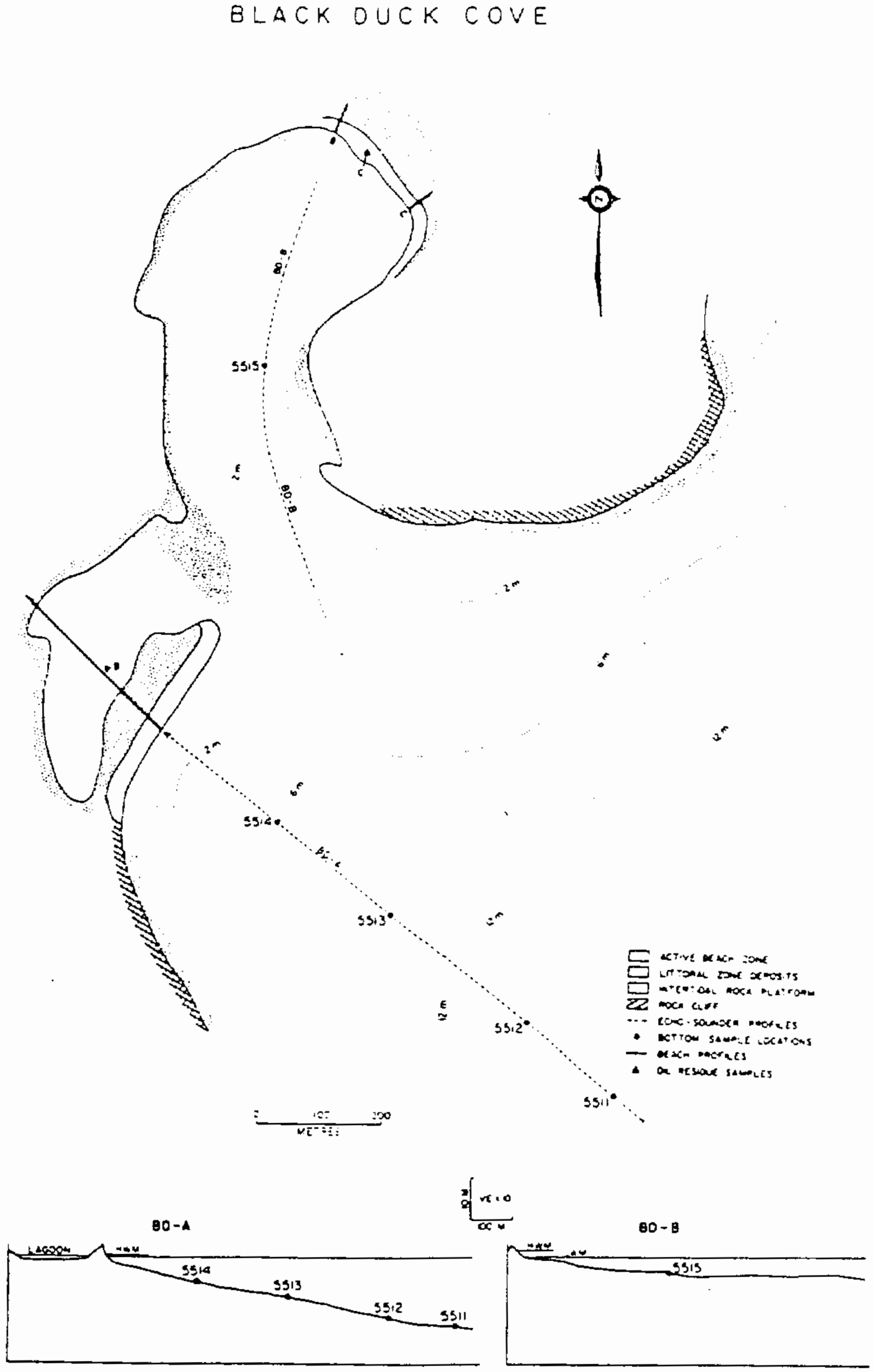


FIG. 11. Black Duck Cove study area, with beach-nearshore profiles on lines A and B. The nearshore profile on line A was surveyed at mid-tide.

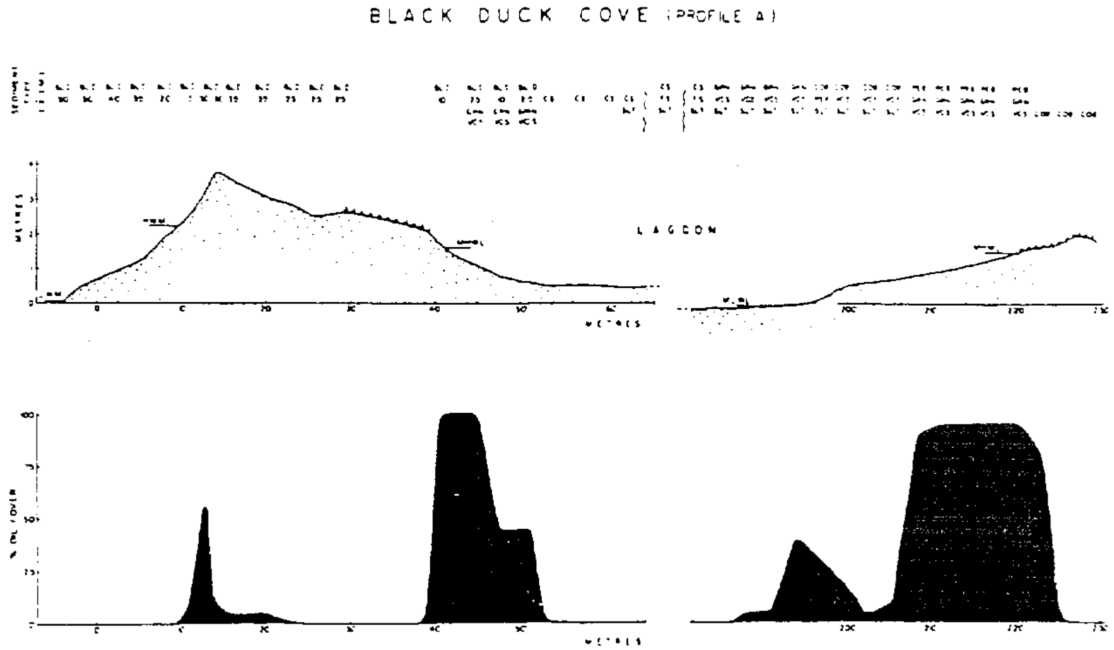


FIG. 12. Beach profile A across the boulder spit and lagoon, Black Duck Cove, located on Fig. 11. The sediment type is based on grain-size estimates taken at a 3-m interval, and the per cent oil cover was determined along the profile line on a 1-m-wide section.

of the spit, the relatively flat sea-floor, which has a gradient of 1:50 (Fig. 11) is covered by sediments that range from sand and boulders to silt, clay, and sand offshore (Table 4). The channel at the distal end of the spit is floored by pebbles, cobbles, and boulders. In the Cove, the bottom sediments are well sorted sands and the beach, which is fronted by a wide sandy low-tide terrace, is composed of medium to coarse grained sand.

In the spring of 1970, the Black Duck Cove area was contaminated by a large oil slick from the ARROW (Drapeau 1973). The manner in which the oil was deposited and degraded in the different environments of this section of coast (the exposed spit, the lagoon, and the Cove beach) is representative of similar conditions observed elsewhere in Chedabucto Bay.

On the exposed side of the boulder spit, oil was deposited above the mean high water mark and some oil was carried over the storm ridge by wave splash. A traverse across the spit and lagoon in July 1973 indicates the extent of the oil cover after three and a half years (Fig. 12). The intertidal zone was not contaminated due to continuous wave action. Above the normal limit of wave action little oil has been abraded, as this zone is only affected during periods of storm waves. On some parts of the ridge oiled material is being buried by clean cobbles and boulders that are thrown up onto the highest parts of the beach (Buckley *et al.* 1974, fig. 17).

The lagoonal side of the spit and the northwestern shore of the lagoon were covered by a thick (10–25 cm) layer of oil following the ARROW disaster. This oil is still present (Fig. 13; and Buckley *et al.* 1974, fig. 18) and is clearly visible on vertical aerial colour photographs obtained in August 1973 (1:8000 scale). There is virtually no wave action in the lagoon due to its small size and because of a bar across the entrance, which is exposed at low tide. In these low energy conditions, physical abrasion of the oil has been negligible and the extent of the oil cover has not changed significantly since 1970.

On the floor of the lagoon, which is usually covered by 10–50 cm of water at low tide, little oil was deposited except where it was trapped by eel grass. In May 1973 at one location, fresh clam holes were observed in the partly encrusted layer of oil and plant shoots were seen growing through the oil in the intertidal zone. On the bar at the mouth of the lagoon, oil is present in the spaces between boulders as a sediment–oil

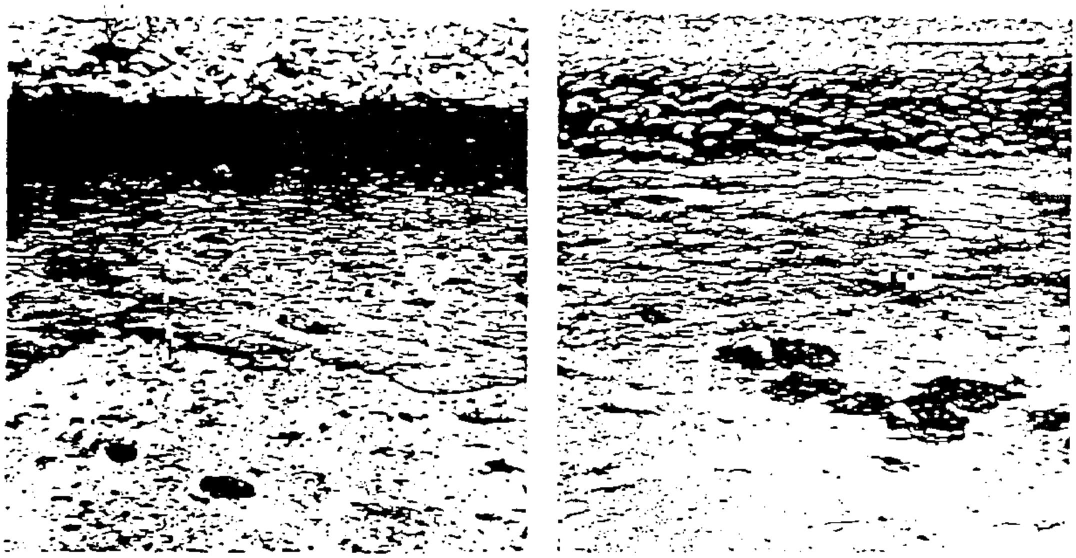


FIG. 13. Oil residues in the upper part of the intertidal zone on the lagoonal side of the boulder spit at Black Duck Cove. Both photographs taken at approximately the same location at low tide: (left) May 1970, scale graduated in 10-cm intervals; (right) May 1973, scale graduated in 5-cm squares. The upper limit of the oil cover is the mean high tide level.

matrix. This asphalt-like material is a mixture of sand granules and oil, and is very resistant to physical erosion.

The sand beach in the Cove was heavily contaminated in 1970 by oil from the ARROW and was subsequently cleaned by mechanical methods (Owens 1971*b*). Following restoration, this beach was recontaminated again by oil from the adjacent lagoon. In 1973 this oil was present as a discontinuous layer, 5–10 cm thick, often mixed with eel grass, and occurred near the high- and low-water tide levels. Individual particles of newly deposited oil were visible on the surface of the beach face slope (average 4 cm in diameter, 1 cm thick, and one per square metre). Iridescence was observed on the surface of the water, on sediments in the lagoon, and on the surface of the Cove beach.

It is apparent that in the relatively moderate energy environment of the Cove beach some reworking, abrasion, and burial of the oil has taken place. However, in the sheltered low energy environment of the lagoon little or no physical abrasion has taken place. In the lagoon, the only physical action results from small choppy waves and from the rise and fall of the water level due to tides and storm surges. In order to measure the chemical degradation of the oil, samples were collected in the lagoon and on the sand beach (Fig. 11). A sample was also collected from near the high water level on the exposed beach at Crichton Island (Drapeau 1973). The results of the analysis of these samples were compared with those from a reference sample of Bunker C from the ARROW. The physical degradation of oil in the littoral zone is dependent largely on the level of wave energy. From the observations at Black Duck Cove and from the chemical analyses of oil residues, it is possible to discuss the degradation of oil in the littoral zone of Chedabucto Bay at a more general scale.

Distribution and Nature of Oil Residues

The geographic distribution of oil along the coastline of Chedabucto Bay, 3½ years after the grounding of the ARROW, is dependent upon (1) the severity of the original contamination, (2) the nature of the shoreline, and (3) the energy conditions at the shoreline. Drapeau (1973) discussed the natural cleaning of the shoreline at Crichton Island from observations between 1970 and 1972 and concluded that oil deposited in the zone of normal wave action is removed rapidly by mechanical energy, but that above the high water and in inlets, physical cleaning of the shore zone is slow.

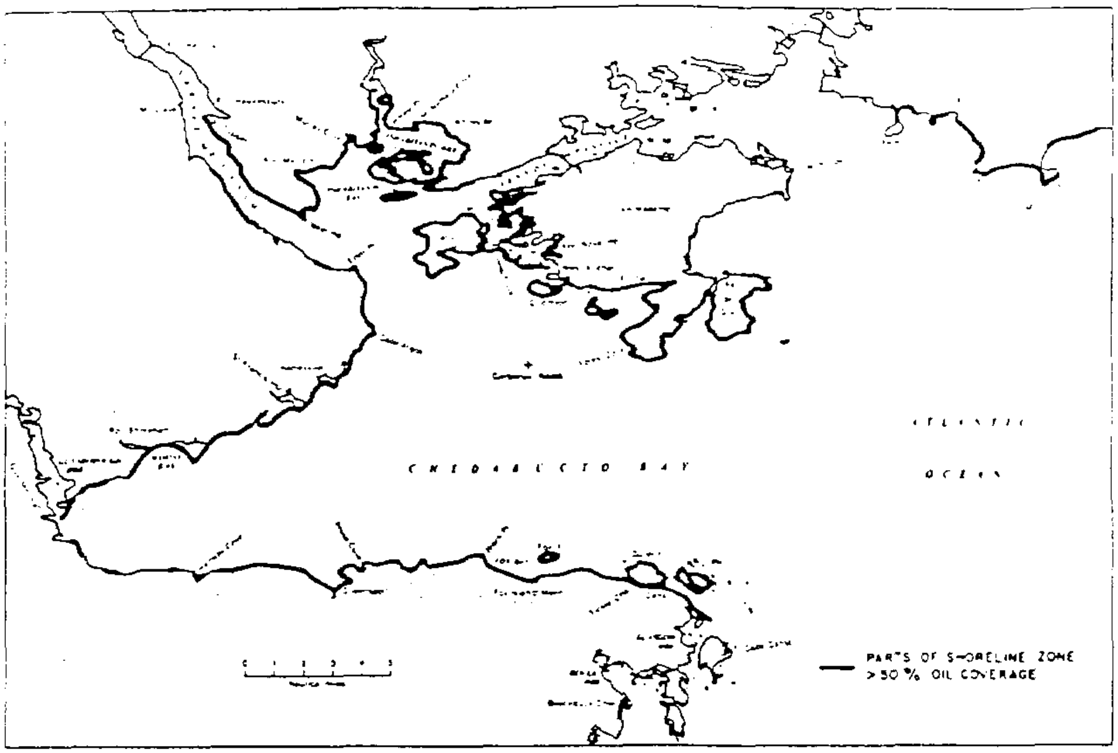


FIG. 14. Distribution of oil residues in the shore zone, spring 1970. This map represents a compilation of all locations where oil was observed between March and June 1970, and indicates the maximum extent of oil distribution in the shore zone.

Distribution of Oil Residues

Few sections along the shoreline of Chedabucto Bay were unaffected by oil from the grounded ARROW (Fig. 14). The area of most severe contamination was along the north shore between Forest Cove, on Isle Madame, and Bear Head, at the entrance to the Strait of Canso. This coast was recontaminated on numerous occasions during the spring and summer of 1970 when large volumes of oil drifted into the sheltered bays and inlets, particularly in Inhabitants Bay. By June 1970, large sections of the coast had been cleaned by normal wave action. An aerial survey does not enable the location of all oil deposits in the littoral zone, particularly where oil was splashed by wave action or reworked into the sediments, and only those areas where the visible cover is greater than 50% are reported (Fig. 15). The west and south coasts of Chedabucto Bay recovered rapidly, as contamination was never severe (except in isolated localities), and these coasts are exposed to wave action. The results of a reconnaissance in October 1973 (Fig. 16) indicate that, even in areas where large volumes of oil reached the shoreline, cleaning has been effective where the coast is open to direct wave action and where the oil was deposited on the beach face slope.

In order to evaluate the effect of different coastal conditions on the spilled oil, chemical and physical properties were analyzed and viscosity measured on residue oil collected from high, medium, and low energy beach environments (Buckley *et al.* 1974; Rashid 1974).

Influence of Coastal Conditions on Weathering of Bunker C Oil

The residual Bunker C oil samples collected from representative low-, moderate-, and high-energy coastal areas of Chedabucto Bay were analyzed to determine the magnitude of changes that have occurred in the chemical and physical properties and also to assess the impact of different environmental conditions on the natural degradative processes.

The hydrocarbons (saturates and aromatics)

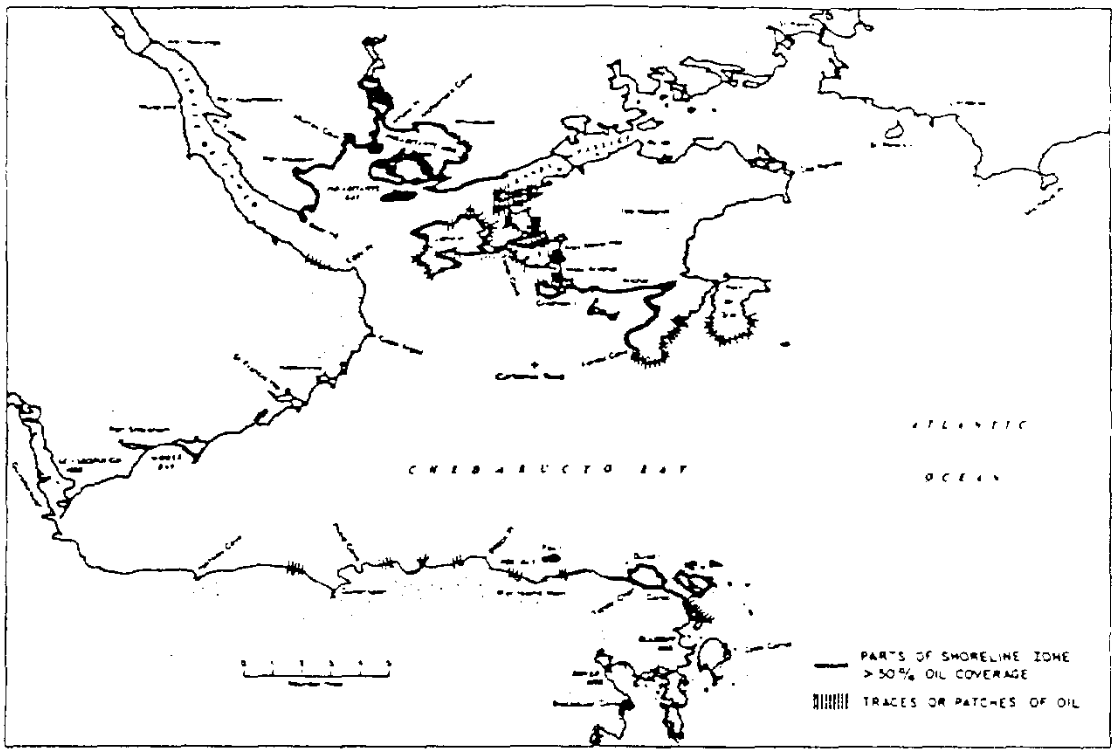


FIG. 15. Oil residues in the shore zone, June 1970, from aerial and ground observations.

and non-hydrocarbons (asphaltenes, resins, and N–S–O compounds), which are the important constituents of crude oil, are affected by the environment in which they are spilled and deposited. The residual oils that have remained on the polluted beaches for 3½ years were fractionated by column chromatography to isolate the various major constituents. The results (Table 5) show that the total hydrocarbon contents of the samples recovered from the low and moderate energy environments (49% and 47%, respectively) are very similar to that of the reference sample (51%) and suggest that the low-energy coastal conditions are ineffective in a fast degradation of oil. On the other hand, there is a drastic reduction (34%) in the hydrocarbon content of the oils recovered from high energy beaches. The ratios of saturated hydrocarbons to aromatic hydrocarbons do not show any variations from one site to another and suggest that the rate of depletion of these two components are more or less similar.

With the weathering of oils through bacterial degradation and/or chemical oxidation, the non-hydrocarbon components are reported to increase substantially (Bailey *et al.* 1973; Blumer *et al.* 1973; McLean and Betancourt 1973). Our data in Table 5 are in agreement with this observation. In the low- and moderate-energy conditions where the weathering processes appear to be very slow and limited, the non-hydrocarbons constituted 51% and 53%, respectively, as compared to 49% in the reference sample or to 66% in the residual oil recovered from the high-energy coast. The chromatograms of gas chromatographic analysis included in Fig. 17 show considerable reduction in the magnitude of peak heights of different samples and reflect upon the chemical changes. Along with the paraffins, the lower-range naphthenes and aromatics are also reduced substantially with the exposure of oil to varying degrees of weathering conditions. The infrared spectroscopic analyses (Fig. 18) also suggest certain changes in the peripheral constituents, especially in the functional groups of residual oils. The absorbance noticed at 2920, 2850, 1470, and 1380 cm^{-1} in all the samples is due to the presence of CH_2 and CH_3 bondings. The samples do not appear to have contamination of any sort from biological sources because

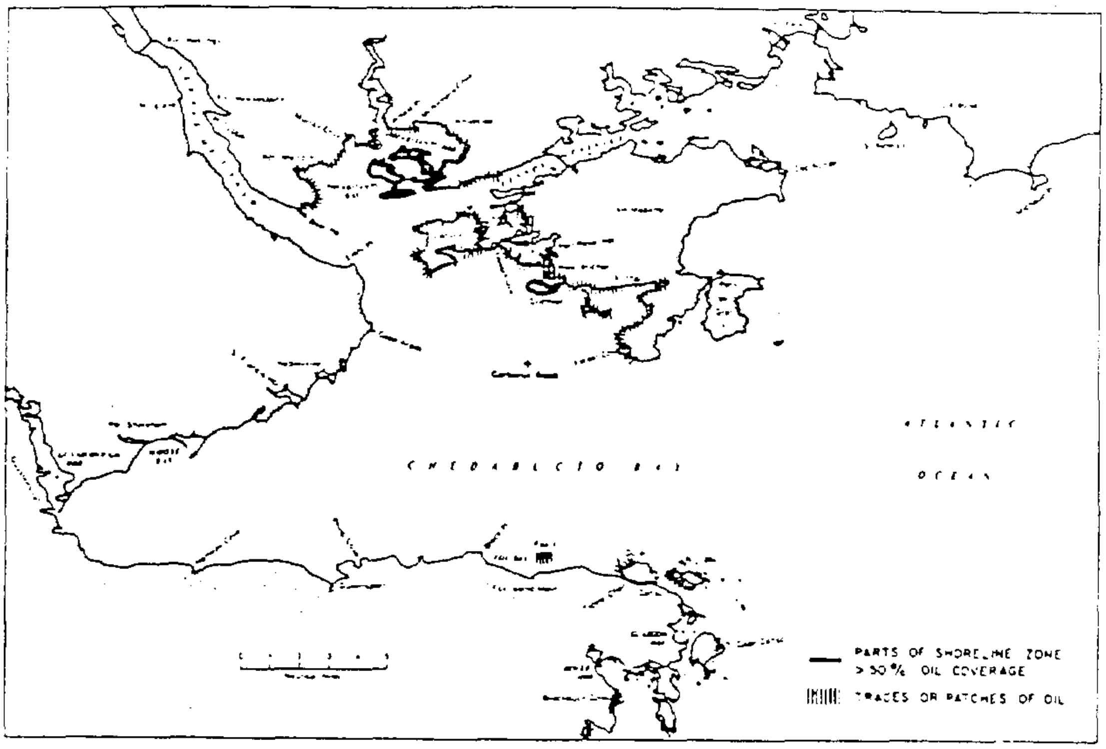


FIG. 16. Oil residues in the shore zone, October 1973, from aerial observations.

the spectra are devoid of characteristic protein (—NH—) absorption at 1605 cm^{-1}. The other changes can therefore be related to oxidative processes. The oxidation process changes the carbonyl and carboxyl content of organic compounds. The absorption noticed in the spectra of all the samples at 1600 cm^{-1} is related to the carbonyl group. The carboxyl function appears at 1775 cm^{-1}. The infrared spectra of reference crude oil sample (A in Fig. 18) does not show any absorption due to carboxyl at 1725 cm^{-1}. The spectra of the low energy sample (B) is similar to reference samples in this region and is devoid of carboxyl peak. The moderate and high energy oils show the presence of carboxyl peaks (1725 cm^{-1} absorption in C and D of Fig. 18).

With increased oxidation, the carbonyl groups disappear. As compared to reference samples, a 60% reduction occurred in the carbonyl content on high-energy coasts. The moderate energy sample showed a 20% reduction. Surprisingly, the highest reduction in carbonyl was noticed in the oil of low energy environments, where oxidation processes are supposed to be low. In this sampling area, the water temperatures were usually 5.5 to 8 °C warmer than the adjoining areas. The high temperature of the shallow waters was probably responsible for the reduction of carbonyl group.

Some physical properties of the residual oils (specific gravity and viscosity) were measured to ascertain the changes with weathering. The data given in Table 5 show considerable variations in the viscosity of oils collected from different coastal conditions. In protected beaches where the oil is still mobile after 3½ years of exposure, the viscosity values are low. In high energy environments where a considerable degree of weathering has taken place, the residual oils, which are usually enriched in non-hydrocarbons, are adhering to the rocks and pebble substrate. The viscosity values of these residual oils are unusually high.

The chemical and physical characteristics of oil residues suggest that the rate of degradation is very slow in the low-energy environments. In sheltered embayments or lagoons (Black Duck Lagoon), which are protected from wave action at all times, viscosity of the oil is very low and the residues have a high hydrocarbon content.

TABLE 5. Chemical and physical characteristics of Bunker C oils obtained from different coastal environments in Chedabucto Bay, Nova Scotia

Characteristics	Bunker C oil	Low-energy coast	Moderate-energy coast	High-energy coast
Hydrocarbons (%)				
Saturates	26	25	23	18
Aromatics	25	24	24	16
Total hydrocarbons	51	49	47	34
Ratio of saturate to aromatic hydrocarbons	1.04	1.04	0.96	1.12
Non-hydrocarbons (%)				
Asphaltenes	20	22	23	22
Resins and NSOs	29	29	30	44
Total of non-hydrocarbons	49	51	53	66
Hydrocarbons/non-hydrocarbons	1.04	0.96	0.88	0.52
Carbonyl (C=O) content, mequiv/g of organic matter	0.55	0.18	0.44	0.22
Physical properties				
Specific gravity	0.963	0.9953	0.9765	0.9823
Viscosity (cP)	19 584	28 600	1210 000	3640 000

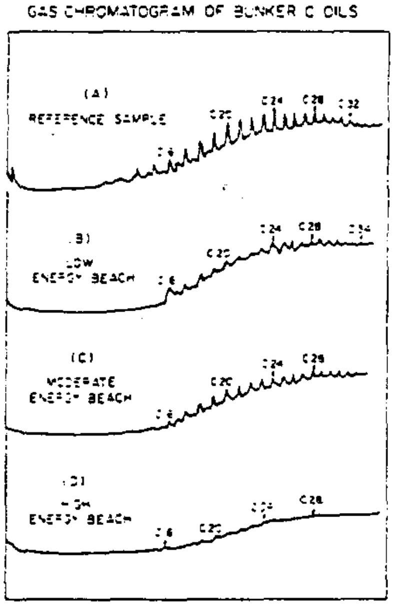


FIG. 17. Gas chromatograms of Bunker C oil samples (after Rashid 1974). (A) Reference Bunker C (stored in the laboratory). (B) Oil extracted from the low energy beach, May 1973. (C) Oil extracted from the moderate energy beach, May 1973. (D) Oil extracted from the high energy beach, May 1973. The location of samples B and C is given on Fig. 11; sample D was collected from the south shore at Crichton Island (Fig. 3).

On beaches that are not directly exposed to the ocean but are subject to infrequent wave action during storms, such as pocket beaches (Indian Cove) or bay-head bars (Black Duck Cove), viscosity is low and the hydrocarbon content remains high. It is evident that the effects of weathering and wave action in these low- and medium-energy environments are a slow process. It is therefore speculated that this type of polluted beach is likely to remain unchanged for a considerable length of time. On open ocean beaches that are exposed to wave action at all times, the oil residues are physically abraded rapidly, are highly viscous, and have a high resin–asphaltene content. In these high energy environments (Black Duck spit; Crichton Island), weathering forces change the composition of the oil substantially and natural processes clean the beaches rapidly.

Conclusions

The selection of methods to restore beaches contaminated by oil should be closely related to the dynamics of the littoral environment and to the type of beach sediment. The removal of sediment from the beaches of Chedabucto Bay, either to restore contaminated sections or for

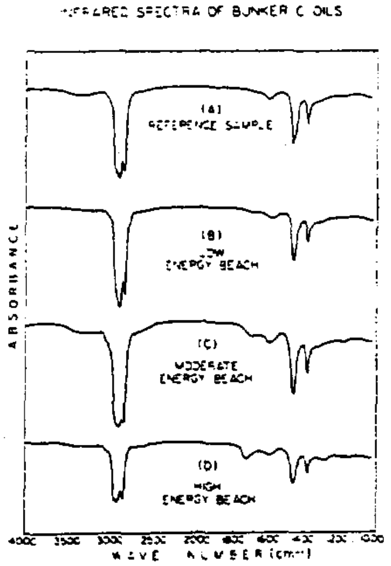


FIG. 18. Infrared spectra of oil samples. All samples were collected at the same location and at the same time as those indicated in Fig. 17 (after Rashid 1974).

construction material, has resulted in permanent retreat of the beach crest in areas where the amount removed exceeds the natural supply of sediment. Rates of sediment accumulation in the littoral zone are low and the practice of sediment removal from the beaches is harmful and should be avoided, particularly in view of the fact that abundant alternate sources are readily available in this region (Grant 1971). At Deep Cove, the long-term retreat of the shore line has been accelerated by the excavation of beach sediments since 1953. Estimates of the sediment supply from erosion of the till cliffs in this area show that approximately 8000 m^3/y of material is supplied to the littoral zone. Only the coarse fraction (approximately 2000 m^3/y) remains on the beaches, which have little sand-sized material, while the silts and clays are transported into deeper water or low energy environments. Sediment removal in the eastern half of Indian Cove resulted in retreat of the beach crest by as much as 20 m during the 12 month period following restoration. Subsequent profiles show that there has been little replenishment of sediment and that a new equilibrium has been established on this beach.

Restoration of contaminated beaches by sediment removal at Hadleyville and at Eddy Point has had no discernable adverse effects on beach stability. These are high energy environments and changes in beach morphology appear to be within the range of normal variation.

Aerial and ground reconnaissance in 1973 to determine the distribution of oil on the shoreline indicated that on exposed coasts, most of the oil in the intertidal zone had been removed by natural processes. Any oil in the intertidal zone on the exposed shores was quickly removed by abrasion due to the impact of waves or to abrasion by the movement of sediment. Where the shore was contaminated above mean high-water mark, natural cleaning has been less effective. On the low-tide terraces, the surfaces of cobbles and boulders have been cleaned by abrasion, but where oil was laid down between the sediments it has mixed with sand, granules, and pebbles to form an 'oil conglomerate' or 'oil matrix', similar to asphalt. This was particularly evident at the entrance to Black Duck Lagoon, at Cape Argos and on Crichton Island. In lower-energy environments, oil drifted onto the shoreline in the intertidal zone and the rate of abrasion of oil has been in direct response to the amount and intensity of wave action. In the lagoon at Black Duck Cove degradation has been negligible, while in the sheltered areas of Inhabitants Bay some natural cleaning is evident even though oil still covers most of the beaches.

Analysis of the physical and chemical properties of oil residues indicates that the rate of degradation appears to be strongly affected by the type of environmental conditions at a given site. In a low-energy environment, the residual oils are only slightly affected and may remain relatively unaltered for years. In a high-energy area, the residual oils are substantially altered to yield a product containing more NSO compounds with high viscosity. Oxidative as well as bacterial degradation appears to influence the chemical and physical characteristics of oils.

It is evident that in high-energy environments, natural processes would have restored the beaches by the physical and chemical degradation of the oils. Physical removal of the contaminated sediments was unnecessary and was particularly inappropriate in areas of limited sediment supply. In low-energy environments, other methods of removing oil are required if it is necessary to restore contaminated shorelines.

Acknowledgments

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Comparison of Oiled and Unoiled Intertidal Communities in Chedabucto Bay, Nova Scotia[1]

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THOMAS, M. L. H. 1978. Comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia. J. Fish. Res. Board Can. 35: 707–716.

During 1976, detailed surveys of four oiled and four unoiled control stations, each subdivided into seven standardized intertidal levels, were carried out in Chedabucto Bay. Seventy-one species were found, 14 unique to control and 9 to oiled locations. Species diversity was uniformly higher at control than oiled stations. No differences in horizontal zonation of major species were apparent. Analysis of abundance and biomass data for the eight stations and seven tidal levels showed a significant overall difference between oiled and control situations. However, no particular station or tidal level was significantly different from any other. Ten species accounted for most of the variance between oiled and control stations. Six of these were more important at controls and four more important at oiled stations. The flora were particularly affected at oiled stations and species dominant on both sedimentary and rocky shores at all but the lowest tidal levels have been reduced. Length and weight data for the clam *Mya arenaria* showed significantly lower values at oiled stations, but that for the periwinkle *Littorina littorea* showed the opposite. The length–weight relationship for both of these species showed a significantly lower increase in weight per unit of length at oiled than at control stations. Oiled stations showed significantly greater concentrations of oil in biota and sediments than unoiled, where concentrations were essentially at background levels.

Key words: hydrocarbon, intertidal community, petroleum, pollution, sediment

THOMAS, M. L. H. 1978. Comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia. J. Fish. Res. Board Can. 35: 707–716.

Au cours de 1976, nous avons effectué des relevés détaillés de quatre stations affectées par le pétrole et de quatre stations témoins non touchées par le pétrole dans la baie Chedabouctou. Chaque station a été divisée en niveaux intertidaux standardisés pouvant aller jusqu'à sept. Nous avons trouvé 71 espèces, 14 particulières aux stations témoins et 9 aux stations affectées par le pétrole. La diversité des espèces est toujours plus élevée aux stations témoins qu'aux stations affectées par le pétrole. Il n'y a pas de différences apparentes dans la zonation horizontale des principales espèces. L'analyse des données sur l'abondance et la biomasse aux huit stations et aux sept niveaux de marée révèle une différence significative dans l'ensemble entre les situations où il y a pétrole et les témoins. Cependant, aucune station ou niveau de marée ne diffère significativement des autres. Dix espèces sont responsables de la plus grande partie de la variance entre les deux groupes de stations. De ces espèces, il en est six qui sont plus importantes aux stations témoins et quatre plus importantes aux stations touchées par le pétrole. La flore est particulièrement affectée aux stations où il y a pétrole et les espèces dominantes sur les rivages sédimentaires aussi bien que rocheux ont été réduites à tous les niveaux de marée, sauf le plus bas. Les données sur la longueur et le poids de la mye commune, *Mya arenaria*, ont des valeurs nettement inférieures aux stations touchées par le pétrole, alors que celles du bigorneau comestible, *Littorina littorea*, démontrent le contraire. La relation longueur-poids de ces deux espèces accuse une augmentation nettement inférieure dans le poids par unité de longueur aux stations touchées par le pétrole par rapport aux contrôles. Les stations affectées par le pétrole ont des concentrations nettement supérieures de pétrole dans la biocoenose et les sédiments aux stations non touchées par le pétrole, où les concentrations sont essentiellement à des niveaux de fond.

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DESPITE the now large number of oil spills there are still comparatively few published accounts of long-term effects on intertidal biota of the oil alone. Where studies have been carried out, most have involved various types of crude and refined oils (Baker 1976; Hampson and Moul 1978; Southward and Southward 1978; Straughan 1977; Straughan et al. 1978) but not Bunker C. Few studies have been carried out in cold climates.

In February 1970 the tanker *Arrow*, loaded with Bunker C oil, grounded on Cerberus Rock in Chedabucto Bay, Nova Scotia. Large quantities of oil escaped and extensive areas of shoreline in the area were contaminated (Anon. 1970). Since that time the distribution and abundance of oil and common intertidal biota have been monitored at a series of seven stations, situated on a variety of shore types on Isle Madame in the northern portion of the Bay.

This experience has provided a long series of observations on a variety of shores, in a cold climate, that were heavily contaminated by Bunker C oil. It should be realized, however, that long-weathered crude and Bunker C residues would be similar because only similar high-boiling point fractions and insoluble compounds would remain. The result of these surveys have been published by Thomas (1972, 1973, 1975, 1977) and Thomas and Harley (1973).

In summary, it was demonstrated that oil adhered strongly to the upper two thirds of the intertidal zone being most persistent at about mean high tide level. After 1970 surface oil declined at varying rates. Attrition was most rapid at lower tidal levels on exposed shores and slowest at high tide levels in sheltered locations. Exposed rocky shores were generally free of surface oil after 3 yr, but considerable oil still persisted at high tide level in sheltered lagoons, 7 yr after initial oiling.

Biotic effects were documented in a number of common species. On rocky shores, where fucoid seaweeds are dominant, the intertidal range of *Fucus vesiculosus* was depressed down the shore, followed by a slow return to normal distribution by 1975. *Fucus spiralis*, which is normally confined to a narrow zone at about mean high tide level, disappeared at study sites and had not reappeared by 1976. By contrast, populations of abundant shore fauna including barnacles, *Balanus balanoides*, and periwinkles, *Littorina littorea*, *L. saxatilis*, and *L. obtusata* did not show changes in distribution and/or abundance except where algal changes affected their habitat.

In sheltered locations, shores are of sand or mud and there, salt marsh cord grass (*Spartina alterniflora*), common at upper intertidal levels, suffered heavy mortalities delayed 1 yr from the initial spill. Recovery was evident 2 yr later and populations appeared essentially normal in 1975. At lower levels on these shores, the soft-shell clam *Mya arenaria* was abundant. This species suffered heavy mortalities where oil cover was extensive but has shown consistent annual recruitment. Mortalities declined with oil but were still above normal in one location during 1976.

These extensive mortalities involving several dominant intertidal species over a long time period suggested that persistent widespread ecological changes had occurred and that a thorough study of the situation was warranted. In 1976 a detailed study was made of biotic communities and oil distribution at four of the initial seven study locations and these were compared to the situation at four unoiled but essentially similar locations in the same general area.

Materials and Methods

STUDY SITES

Figure 1 shows the locations of the four oiled and four control sites all of which were situated on Isle Madame. Table 1 lists locations and shore types for the four pa

Pairs of stations were selected to be similar, as far possible, in (1) exposure to wind and sea, (2) subst type and distribution, (3) a similar shore slope, and biotic characteristics.

SURVEYING AND SUBSTATION SELECTION

At each station a transect, to act as a reference in distributional studies and a central line in population studies was selected to run a right angle to the mean water lin *Heights of all points along this transect were determin* with reference to mean low water using the method described by Thomas (1974). The intertidal distribution

TABLE 1. Characteristics of study locations.

Oiled		Control		
Station location	Width[a]	Location	Width	Substrate
1. Petit Barachois	14	Bewes Pond	8	Bedrock HW
2. Janvrin Lagoon	70	Potato Island	30	Muddy sand HW Sandy mud LW
3. Crichton Island	21	Beak Point	65	Mainly bedrock Some sand HW
4. Janvrin Lagoon	25	Potato Island	21	Muddy sand HW Sandy mud LW

[a] Horizontal distance in metres, high water level (HW) to low water level (LW).

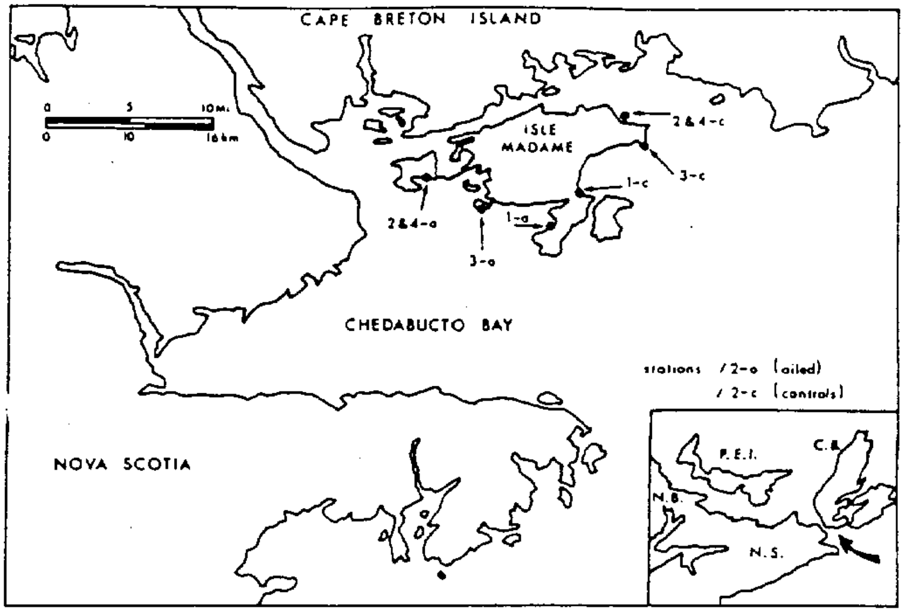

FIG. 1. Chedabucto Bay area of Nova Scotia showing locations of oiled and control study stations.

shore biota were determined in a belt extending 0.5 m both sides of the line.

Substations for quantitative studies of biotic communities were established on the line at the following tidal levels where possible: —0.3 m, 0.0 m (mean low water), 0.3 m, 0.65 m (mean tide level), 1.0 m, 1.3 m (mean high water), and 1.9 m (extremely high water). Some levels were not available for study at all locations due to local topography.

COMMUNITY STUDY METHODS

At each substation the biotic community was described by removing all biota within a quadrat of 0.1 to 1.25 m^2 (mean 0.43 m^2, $n = 37$). The size of the quadrat was adjusted to give a total sample of about 1 kg fresh weight except where biota were sparse. In sedimentary locations sediment was screened through 4-mm mesh to a depth of [illegible] cm. From these collections, biomass was determined for each species on a fresh weight basis and the number of individuals of each species was counted. Samples were then frozen at —20°C and later dry weight and ash free dry weight biomass for each species were determined. All statistics were adjusted to represent samples of 1 m^2.

Outside the quadrat but at the same tidal level, samples of 50 *L. littorea*, 50 *M. arenaria*, and/or 1 kg of *S. alterniflora*, whichever were present, were collected at random for measurement of length and weight of individual fauna and for oil content analysis of all species.

SAMPLE COLLECTION AND SURFACE OIL MEASUREMENT METHODS

In sedimentary locations cores of 5.5 cm diam and at least [illegible] cm long were taken by hand corer pushed vertically into the sediment to a natural stop. These samples were kept frozen at —20°C for later analysis. On rock, the percentage oil cover was measured using various sized quadrats. All sample locations were photographed.

OTHER METHODS

At substations at station 2-oiled, where *M. arenaria* mortalities had previously been measured (Thomas 1977), mortalities were again estimated. A core for oil analysis was taken at substation 2 where oil was still visible; samples of living and freshly dead clams (bodies present in shells) were collected for oil analysis from substations 1–3. A sample for estimate of abundance was taken from a point at station 2 previously used for this purpose (Thomas 1977).

OIL EXTRACTION AND ANALYSIS METHODS

Two to 20 g of wet sediment from the upper 10 cm of the core were wet weighed in a tared, rinsed 50-mL glass centrifuge tube, and slurried with pentane-extracted distilled water (5 mL). The slurry was then extracted twice with 10 mL redistilled pentane for 20 min on a Burrell Wrist-action shaker at 800 oscillations/min.

The sediment–pentane mixture was centrifuged 10 min to separate the phases. The pentane supernatant was drawn off and the extraction repeated. The pentane extracts were pooled, concentrated to ca 5 mL (N-Evap), and transferred to a graduated centrifuge tube. Sufficient pentane was added to yield a final volume of 10.0 mL hydrocarbon extract in pentane. The extracted sediment was dried overnight in a drying oven at 110°C, and the dry weight recorded.

Hydrocarbon concentration in the pentane extract was determined fluorometrically (λ_{exc} 310 mμ, λ_{em} 374 mμ, Perkin-Elmer MPF-2A fluorescence spectrophotometer). Final concentrations were expressed as micrograms *Arrow* Bunker C oil "equivalents" per gram dry weight of sediment.

TISSUES

All organisms were first thoroughly cleaned and rinsed under running tapwater to remove all traces of organic

TABLE 2. Species occurring in at least ¾ of all stations of each shore type and their mean upper and lower limits (metres above mean low water). ST, extending subtidally.

Species	Upper limit	Lower limit
	Rocky shores	
Cladophora sp.	1.04	ST
Fucus vesiculosus	1.36	ST
F. serratus	0.00	ST
Ascophyllum nodosum	0.70	ST
Chondrus crispus	0.20	ST
Sertularia pumilla	0.41	0.19
Balanus balanoides	1.15	0.21
Gammarus oceanicus	0.76	ST
Acmaea testudinales	0.34	ST
Littorina saxatilis	1.35	0.08
L. obtusata	1.23	ST
L. littorea	1.20	ST
Thais lapillus	0.72	ST
Mytilus edulis	1.39	
	Sedimentary shores	
Spartina alterniflora	1.42	0.85
Cladophora	1.19	ST
L. saxatilis	1.66	ST
L. littorea	1.38	ST
Mytilus edulis	1.12	ST

TABLE 3. Number of species and species diversity index from oiled and control stations.

Station no.	Number of species (diversity index^a)	
	Oiled	Control
	Rocky shores	
1	29 (0.56) ((0.30))	30 (0.26) ((0.76))
3	23 (0.34)	33 (0.52)
	Sedimentary shores	
2	13 (0.04)	17 (0.10)
4	9 (0.04)	13 (0.05)

[a] Shannon-Weiner diversity index (Pielou 1966) based on abundance as a measure of importance.

TABLE 4. Species unique to oiled and control sites on rocky and sedimentary shores.

Oiled	Control
Rocky shores	
Xanthoria parietina	*Parmelia* sp.
Verrucaria sp.	*Elachista fucicola*
Gammarus setosus	*Punctaria latifolia*
Strongylocentrotus droebachiensis	*Petalonia palmata*
Podoceropsis sp.	*Polysiphonia lanosa*
Chironomidae	*P. urceolata*
	Taelia felina
	Cyathura polita
	Gammarus angulosus
	Hydrobia minuta
Sedimentary shores	
Oiled	Control
Scoloplos fragilis	*Juncus balticus*
Lineus ruber	*Fucus vesiculosus*
Onchidoris aspersa	*Haminoea solitaria*
	Macoma baltica

detritus and sediment. They were then rinsed thoroughly with acetone. Bivalves and snails were removed from their shells and again rinsed thoroughly with acetone. After air-drying for 5–10 min the samples were minced into tared, prerinsed, glass test tubes, and the wet weight of tissue recorded.

The tissue sample was homogenized for 2 min in 25 mL redistilled methanol–benzene with a Polytron Ultrasonic blender. The homogenate was filtered through prerinsed filter paper, and the remaining tissue homogenate was re-extracted with methanol–benzene. The final extracts were pooled in a flat-bottom boiling flask.

To the combined filtrates 20 mL of pentane-extracted distilled water and 2 N KOH in methanol were added to yield a final 0.5 N solution. This mixture was saponified for 2 h by refluxing. The saponified sample was put through a series of aqueous NaCl washes and pentane extractions to yield a final single pentane-benzene phase. This extract was dried overnight with anhydrous Na_2SO_4.

The sample was concentrated to ca 5 mL, transferred to a graduated centrifuge tube, and sufficient pentane added to yield a final volume of 10.0 mL tissue hydrocarbons in pentane.

Hydrocarbon concentration was determined fluorometrically (λ_{exc} 310 mμ, λ_{em} 374 mμ, Perkin-Elmer MPF-2A fluorescence spectrophotometer). Concentrations were expressed as micrograms *Arrow* Bunker C oil "equivalents" per gram wet weight of tissue.

All glassware used was rinsed with double distilled solvents. All solvents used were redistilled in glass. *Arrow* Bunker C, courtesy of Dr E. Levy, Bedford Institute of Oceanography, served as standard.

STATISTICAL METHODS

Results from the analysis of the communities at all 37 substations were analyzed in a nested analysis of variance. The analysis was set up to compare oiled and control stations as follows: (1) each tidal level (substation) for control stations was compared to the same level at oiled stations, (2) each control station (substations pooled) was compared to each oiled station, (3) pooled control stations were compared to pooled oiled stations, (4) each species at control stations was compared to the same species at oiled stations. Probabilities were obtained from the *F* values between two variances.

Results

INTERTIDAL BIOTA

Seventy-one species of animals and plants were identified from the collections, the highest number from any one station being 33 species. Many of the common species showed characteristic intertidal zonation. The

TABLE 5. Summarized abundance and biomass data for Chedabucto Bay study stations.

	Stn. 1		Stn. 2		Stn. 3		Stn. 4	
	Oiled	Control	Oiled	Control	Oiled	Control	Oiled	Control
Fauna individuals/m^2	14776	1963	17	157	144	1136	8	103
Fauna fresh biomass g/m^2	59	58	13	17	67	3	5	190
Fauna decalcified dry biomass g/m^2	11.9	10.3	2.7	4.0	9.0	0.4	0.9	17.1
Fauna ash-free biomass g/m^2	8.0	7.8	2.3	2.3	6.2	0.4	0.7	9.6
Flora fresh biomass g/m^2	2684	6498	337	2578	710	4941	1862	3542
Flora dry biomass g/m^2	615	1787	69	455	143	1089	315	600
Flora ash-free dry biomass g/m^2	437	1453	44	359	109	852	276	443

information is summarized in Table 2. The data do not show any consistent differences in zonation of common species between oiled and control sites.

Table 3 shows the number of species occurring at each station together with the Shannon-Weiner diversity index (Pielou 1966) calculated using both biomass and abundance as a measure of importance. The number of species at control sites was always as high or higher than at oiled ones of the same substrate type.

When oiled and control sites were compared for species found at only one or the other, it was found that on rocky shores, 10 species were unique to controls and 6 to oiled; on sedimentary shores, 4 to controls and 3 to oiled. None of these is really a common species in the area. Data are summarized in Table 4.

Table 5 presents summarized abundance and biomass data for all stations. So that comparisons are valid, only substations that were common to pairs of stations were included. The statistical analysis of the complete raw data for the 12 most common species revealed that there was a highly significant difference in biotic importance between oiled and control stations ($P < 0.05$). This difference was mainly attributable to significant differences in the importance of a few common species between oiled and control stations. These differences are summarized in Table 6.

The most obvious large difference was that of the biomass of flora between oiled and control. At oiled stations the mean fresh weight biomass was 1398 g/m^2 whereas at controls it was 4390 g/m^2 (P for difference <0.005.). The analysis did not show any particular stations or levels to differ significantly from each other in producing the observed effects.

TABLE 6. Summary of significant differences in importance of species at oiled and control stations.

Species	P	Difference
A. nodosum	<0.005	Biomass higher at control
M. edulis	<0.005	Numbers higher at oiled
L. obtusata	<0.01	Numbers higher at control
L. saxatilis	<0.05	Numbers higher at control
L. vincta	<0.05	Numbers higher at oiled
F. serratus	<0.1	Biomass higher at oiled
G. oceanicus	<0.1	Numbers higher at oiled
C. crispus	<0.1	Biomass higher at control
F. vesiculosus	<0.1	Biomass higher at control
T. lapillus	<0.1	Numbers higher at control

POPULATION STATISTICS FOR *Littorina littorea* AND *Mya arenaria*

The analysis of length and weight data for collections from oiled and control sites revealed several consistent and highly significant differences (Table 7). Statistical analyses confirmed that the overall differences in both length and weight between oiled and control sites were highly significant ($P < 0.001$) for both *L. littorea* and *M. arenaria*. Comparisons between identical levels at oiled and control station pairs revealed similarly significant differences.

Tests for differences between all possible oiled-control, substation pairs at station 1 for both length

TABLE 7. Summarized length and weight data for *Littorina littorea* and *Mya arenaria* collected from oiled and control substations.

Station	Level (m)	Mean length (cm)	Mean wt (g)
	Littorina littorea		
1 oiled	0.3	1.71	1.7
1 oiled	0.65	1.57	1.5
3 oiled	0.3	1.64	1.6
1 control	−0.3	1.30	0.8
1 control	0.0	1.24	0.5
1 control	0.3	1.38	1.1
3 control	0.0	1.71	1.9
Overall oiled	—	1.64	1.6
Overall control	—	1.41	1.1
	Mya arenaria		
2 oiled	0.65	2.91	3.6
4 oiled	0.65	2.54	2.7
2 control	0.65	3.57	8.3
4 control	0.3	3.15	6.2
Overall oiled	—	3.36	3.2
Overall control	—	2.73	7.3

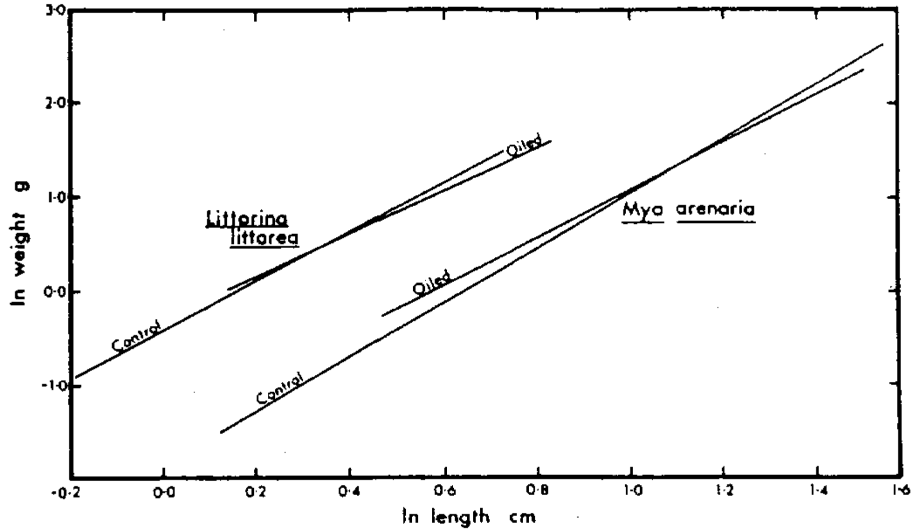

FIG. 2. Calculated length–weight regression lines for *Littorina littorea* and *Mya arenaria* from oiled and control stations.

and weight in *L. littorea* showed significant differences at better than the 99.9% level ($P < 0.001$) (12 cases). Tests between oiled substations showed no differences significant at this level (two cases). Tests between control substations showed only three of eight cases with differences significant at this level. At station 3 tests on length and weight of *L. littorea* (two cases) showed significant differences ($P < 0.001$) between oiled and control sites.

In the case of *M. arenaria* all oiled-control comparisons between substations, at each station, showed similarly significant differences ($P < 0.001$).

In summary, *L. littorea* at oiled stations were longer (mean 1.64 cm) and heavier (mean 1.6 g) than specimens from control stations (mean length 1.41 cm, weight 1.1 g). *Mya arenaria* at oiled stations were shorter (mean 2.72 cm) and lighter (mean 3.2 g) than specimens from control stations (mean length 3.36 cm, weight 7.3 g).

Calculation of the length–weight relationships for *L. littorea* and *M. arenaria* for control and experimental locations (pooled substation data) yielded the following equations (weight, grams; length, centimeters):

M. arenaria oiled ln wt. = 2.47 (ln length) −1.43
M. arenaria control ln wt. = 2.91 (ln length) −1.87
L. littorea oiled ln wt. = 2.27 (ln length) −0.30
L. littorea control ln wt. = 2.64 (ln length) −0.42

Differences between regression coefficients are significant at the 99% level ($P < 0.01$) for *M. arenaria* and at the 95% level ($P < 0.05$) for *L. littorea*. Regression lines are shown in Fig. 2. Both *L. littorea* and *M. arenaria* increase in weight more rapidly with length at control than at oiled stations.

Population density values for *L. littorea* and *M. arenaria* at the substations from which they were collected are shown in Table 8. These results show no significant differences between oiled and control stations.

Figure 3 shows length-frequency histograms for pooled samples of *L. littorea* and *M. arenaria* from oiled and control situations. These histograms do not show any notable differences between oiled and control situations other than different modes.

OIL IN SEDIMENTS AND BIOTA

The quantities of oil extracted from sediment and biota samples from oiled and control stations are presented in Table 9. The sediment analyses confirmed that sediments at oiled stations were heavily contaminated with oil, whereas those at control stations showed only background levels. At oiled stations, oil concentrations were highest at mean high water, but still very high at mean tide level.

The table also presents results for two additional sediment samples. One was from station 2-oiled at a location where clam mortality has been monitored since 1970 and had persisted through 1976 (Thomas 1977). There oil concentration was very high. A second additional sample was from Janvrin Harbour Lagoon which was only lightly oiled. There, oil concentrations were intermediate.

The oil content of the tissues of *L. littorea* from oiled locations averaged 12.18 µg/g whereas from control it averaged 5.33 µg/g. These values are significantly different ($P < 0.01$). An additional sample from Arichat Church, an oiled location used in previous studies was also higher than controls at 12.0 µg/g.

In the case of *M. arenaria*, the tissues of living specimens from oiled sites averaged 157.34 µg/g and from control sites, 60.73 µg/g. Individual values showed great variation and these differences were not significantly dif-

TABLE 8. Population density (no./m²) for *L. littorea* and *M. arenaria* from oiled and control substations.

Station	Level (m)	No./m²
	Littorina littorea	
1 oiled	0.3	210
2 oiled	0.65	339
3 oiled	0.3	305
1 control	−0.3	860
2 control	0.0	920
3 control	0.3	470
4 control	0.0	22
Overall oiled	—	284.7
Overall control	—	568.0
	Mya arenaria	
2 oiled	0.65	4
4 oiled	0.65	248
2 control	0.65	16
4 control	0.3	222
Overall oiled	—	126
Overall control	—	119

ferent. However, Gilfillan and Vandermeulen (1978) obtained much higher values from clams from the same oiled locations and the additional samples given here from newly dead clam tissues averaged 650.8 $\mu g/g$ which is significantly higher than control levels ($P < 0.05$).

With *S. alterniflora*, samples from oiled locations showed a mean of 15 134 $\mu g/g$ oil in their tissues while control grass showed a mean of 28.2 $\mu g/g$, the concentrations being highly significantly different ($P < 0.005$).

The amount of surface oil persisting on the surface at various tidal levels was generally low at oiled locations and always zero at controls. At station 1 no surface oil was present below the 1-m level and less than 1% of the shore between there and high water was contaminated. The situation at station 3 was similar except that the zero oil level was 0.65 m. At station 2 there was no surface oil below 1.0 m, less than 1% from 1.0 to 1.3 m, and 30% from 1.3 to 1.9 m. At station 4 there was no surface oil below 1.1 m, 5% from 1.1 to 1.6 m and less than 1% from 1.6 to 1.91 m.

A sample of *M. arenaria* from station 2-oiled for comparison with previous samples from this location (Thomas 1977) showed an abundance of 560/m².

Discussion

Ecologists attempting to determine the affects of oil spills in poorly studied locations face particular problems. Data on normal intertidal communities is usually fragmentary or absent and access to the coastline is often difficult. These problems occurred in Chedabucto Bay and were compounded by the fact that the spill occurred in the coldest part of winter when sea-ice formation was considerable and, consequently, many shores were impossible to observe or sample. It was even difficult to determine the exact extent of oil contamination because of movement in and under ice (Anon. 1970). At the time, it was impossible to make precise, detailed studies of newly oiled situations. Consequently, it was the spring of 1970 before areas were examined in detail and by then biotic effects had already clearly occurred (Thomas 1973).

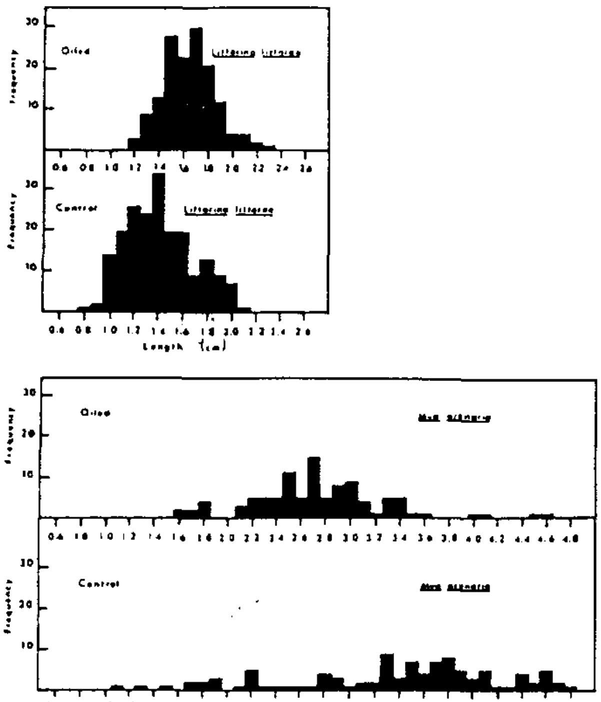

FIG. 3. Length-frequency histograms for *L. littorea* and *M. arenaria* from oiled and control stations.

The difficulty of providing an adequate control situation was aggravated by these conditions and it was decided that a double approach would be used. Detailed surveys of six sample sites would be repeated as often as practicable on the assumption that with time, oil effects would change and the biota would respond. It was assumed that eventually intertidal communities would return to a normal condition and therefore provide a self-control. A second control was attempted in the comparison of oiled sites with a reasonably close-by unoiled control. Unfortunately, however, this location was contaminated with remobilized oil and also suffered extensive natural storm damage.

The method of using time as a control was shown to be useful but lacking in sensitivity (Thomas 1977). Only large changes in common organisms could be correlated with oil pollution. It must also be realized in using this method that climatic changes may cause progressive biotic changes. Such cases have been described by Crapp (1971), Baker (1976), and Straughan et al. (1978). Nevertheless, it was possible to attribute large

TABLE 9. Quantities of oil extracted from sediments and biota from Chedabucto Bay subsamples. (Sediments, micrograms per gram dry weight; biota, micrograms per gram wet weight.)

Station	Level (m)	Oil extracted (duplicates) µg/g ABC equivalents	
	Sediments		
2 oiled	0.65	254.26	90.27
2 oiled	0.70	11.52	0.81
2 oiled	1.00	11 020.22	9 923.81
2 oiled	1.30	19 926.33	16 129.79
2 control	0.30	0.31	0.32
2 control	0.65	1.98	3.71
2 control	1.00	5.54	5.20
2 control	1.30	0.88	0.24
2 control	1.91	0.81	0.59
4 oiled	0.65	2 644.92	74.42
4 oiled	1.00	4 952.92	9 493.66
4 oiled	1.30	18 433.48	25 577.74
4 control	0.3	0.35	0.21
4 control	0.65	0.26	0.24
4 control	1.00	0.00	0.00
	Additional sediment samples		
2 oiled SS no. 2		11 747.77	10 344.47
Janvrin Hbr. Lagoon	0.65	168.62	185.19
	Littorina littorea		
1 oiled	0.30	11.0	11.3
1 oiled	0.65	18.2	19.0
1 control	−0.30	6.9	10.2
1 control	0.00	4.6	5.8
1 control	0.30	6.0	4.0
3 oiled	0.30	5.9	7.7
3 control	0.00	2.5	2.5
	Additional L. littorea samples		
Arichat Church — oiled	0.00	9.2	16.6
	Mya arenaria		
2 oiled	0.65	52.4	48.8
2 oiled	0.70	51.0	34.7
2 control	0.65	47.5	143.3
4 oiled	0.65	167.2	110.7
4 control	0.30	29.2	22.9
	Additional M. arenaria samples		
2 oiled	SS no. 1 alive	56.1	73.3
2 oiled	SS no. 2 alive	183.3	981.0
2 oiled	SS no. 2 newly dead	946.5	882.3
2 oiled	SS no. 3 alive	59.1	69.9
2 oiled	SS no. 3 newly dead	123.6	—
	Spartina alterniflora		
2 oiled	1.3	10 351.8	9 028.7
2 control	1.6	67.8	15.0
4 oiled	1.0	20 943.5	20 215.4
4 control	0.65	15.4	14.7

changes in common and important species in Chedabucto Bay to oil pollution. The dominant fucoid algae of rocky shores were reduced in vertical distribution, salt marsh grasses suffered delayed mortalities, and soft shell clams in lagoonal sediments declined in number. It was also shown that mortalities may be delayed up to several years from initial oiling as was the case with salt marsh cord grass. It was also demonstrated that common fauna such as periwinkles and barnacles were not obviously affected and that in the case of barnacles reproduction was consistent even while contamination was heavy.

The detailed comparison of four oiled and four control stations described here has yielded further useful information and was also used by Straughan (1977) to identify effects of the *Metula* crude oil spill in the Strait of Magellan. This method, however, also lacks sensitivity. The basic problem is the large fundamental variability of shallow water marine and intertidal communities. Even in a single location, such associations show high variability only a part of which can be correlated with known physical variables (Hughes and Thomas 1971a, b). When control and experimental sites must be geographically separated the unaccountable variance becomes even higher. This tends to mask the more subtle but nevertheless important effects.

Both the time and space control techniques for delimiting the long-term effects of oil on intertidal communities are valid and useful. The information obtained is useful in predicting the effects of spills and cleanup procedures in diverse habitats. When combined with experimental data it suggests profitable future research projects. However, only comparatively large changes are documented by these methods and such changes are likely to have more widespread ecological effects than can be readily observed.

This study has shown several additional biotic effects of oil in Chedabucto Bay, and confirmed previous ones. No significant differences in intertidal distribution of species between oil and control sites were observed. Thomas (1977) had previously observed that such differences had disappeared by 1976. There was, however, a very consistent difference in the species diversity, as shown by the number of species found, between oiled and control sites. This situation is typical of communities stressed by pollution but it is interesting that the difference persists over 6 yr after the disaster, especially since most shores are essentially oil free. Diversity indices did not prove useful because results varied widely according to the measure of importance used to calculate them. Biomass is the most useful comparative measure of species importance in intertidal areas since many species are compound, colonial, or encrusting and difficult to count. However, diversity indices based on biomass give low and misleading values. In the case of station 1, the use of biomass and numbers as measures of importance gave opposite results (Table 3). Another aspect of diversity differences was shown by the larger number of species unique to control than oiled stations on rocky and sedimentary shores. While some of these occurrences are undoubtedly by chance, others may be sensitive species. Of particular interest may be *Polysiphonia lanosa*, a red alga epiphytic/parasitic on *Ascophyllum nodosum*, which is normally abundant, but was not found in oiled station samples.

Computer analysis of the complex matrix of data generated by the experiment yielded relatively few significant differences. The overall difference in importance value between oiled and control situations was highly significantly different but no one level, group of levels, or stations showed significant differences from others. The data show that the biomass of flora (algae and flowering plants) was very significantly lower at oiled sites. This is consistent with large effects on flora described previously by Thomas (1977). However, this new data shows a more widespread effect. Three algae had significantly higher biomass levels at control than oiled situations. These were *A. nodosum*, the knotted wrack, *Chondrus crispus*, Irish moss, and *F. vesiculosus*, bladder wrack. The first two are common and of commercial importance; the latter is often dominant on exposed rocky shores. Only one alga, *F. serratus*, which occurs in the lower shore was significantly more important at oiled than control stations. All the fucoid algae species present in the area have now been shown to be affected by oil pollution.

Among the fauna the differences were generally less noticeable. Three species of gastropods showed significantly higher numbers at control sites. These were two periwinkles, *L. obtusata* and *L. saxatilis*, and the dog whelk *T. lapillus*. Showing the opposite trend were the bivalve *M. edulis*, the blue mussel, the gastropod *L. cincta*, the chink shell, and the amphipod crustacean *Gammarus oceanicus*. It is interesting that the two periwinkles were less abundant at oiled sites, because the third common member of this genus, the common periwinkle *L. littorea*, which was equally abundant throughout, did show significant length, weight, and length–weight ratio differences between oiled and control sites.

The two most common animals of rocky and sedimentary shores, *L. littorea* and *M. arenaria*, were selected for size studies. Neither showed significant differences in abundance between oiled and control sites but differences in length and weight were highly significant. *Littorina littorea*, the common periwinkle, was longer and heavier at oiled sites, whereas the soft-shell clam *M. arenaria* showed the opposite. Both, however, showed a slower increase in weight per unit of length at oiled than at control situations. It is known that oil affects both species. *Littorina littorea* shows increased crawling speed and metabolic rate with low doses of Bunker C oil (Hargrave and Newcombe 1973) and narcotization at higher levels (Griffith 1972) but generally not mortality. *Mya arenaria* may show increased or decreased metabolic rates and feeding rates in varying degrees of oil production (Anderson 1972; Avolizi and Nuwayhid 1974; Stainken 1978). Heavy pollution often results in significant mortalities (Michael 1977; Thomas 1977), and population declines associated with oil pollution have been demonstrated in Chedabucto Bay and elsewhere. It appears that oil pollution also restricts growth in this species (Gilfillan and Vandermeulen 1978), and alters the length–weight ratio. Growth in weight is apparently reduced more than growth in length. Length frequency studies show that the smaller mean size in oiled areas is not caused by large numbers of small clams. The periwinkles showed a similar affect in the length–weight relationship but individuals in oiled locations were significantly longer and heavier than at control sites. Again length–frequency determinations suggested a growth rate effect rather than a population structure effect. The reason for the difference could be associated with the algal changes observed. *Littorina littorea* browses on rock surfaces and reduction in algal biomass may well result in increased growth of microflora that was formerly shaded. It is noteworthy that recruitment to populations of species adversely affected by oil has not been affected. Settlement and growth have been observed in *Fucus* sp., *M. arenaria*, and *Balanus balanoides* annually since the spill (Thomas 1977). Apparently in affected species the postsettlement period is most vulnerable with observed effects on both growth and survival.

Oil analyses of sediments and biota were useful in confirming the general information regarding the oil pollution situation at oiled and control sites. Sediments from oiled locations proved to still contain very high concentrations of oil, the highest being 2.5% at high tide level at lagoonal station 4. Oil concentrations at midtide levels in lagoons were generally an order of magnitude lower, but still high. In these locations visible surface oil remains only at high tide level.

Oil concentrations in animals were significantly higher at oiled than control situations but not strikingly so. Other data for the same general areas show much higher levels in biota (Gilfillan and Vandermeulen 1978). It was noteworthy that the oil concentration in living clams from a substation at station 2 where mortality continues to be above normal (Thomas 1977) were very high, and levels from newly dead clam tissues from this location were even higher. There is no doubt that clam mortalities are associated with oil contaminated sediments and that oil concentrations are higher in dying and dead clams than in others.

Bunker C oil is clearly implicated in the mortalities of several dominant and important intertidal species in Chedabucto Bay. Of particular concern are reductions in abundance, biomass, and distributions of several major primary producers. Such changes alter the energy flow patterns in the communities and inevitably have broad ecological effects. On the shores of southern England, where algae and animals suffered heavy mortalities following the cleanup of the *Torrey Canyon* spill, Southward and Southward (1978) have documented large unbalanced changes in the biota, which may take a long time to stabilize. Mortalities in Chedabucto Bay were not nearly so extensive as in England but did affect all shores studied. The great increase in common periwinkle size on oiled shores is perhaps a good example of a consequent trophic change; others are no doubt occurring but difficult to document. Further study may give useful information.

Studies in Chedabucto Bay allow us to predict major biotic changes that would occur following a similar spill. There is still a problem, however, in making recommendations concerning cleanup. On rocky shores evidence suggests that cleanup measures would not hasten recovery and might even delay it, since their biotic effects would be as harmful as those of the oil. In sheltered sedimentary locations, however, oil is much more persistent and becomes incorporated deep into sediments where degradation is slow. If cleanup methods for lagoons could be improved so that oil could be removed without sediment penetration or disturbance, cleanup should help to minimize oil pollution effects.

Acknowledgments

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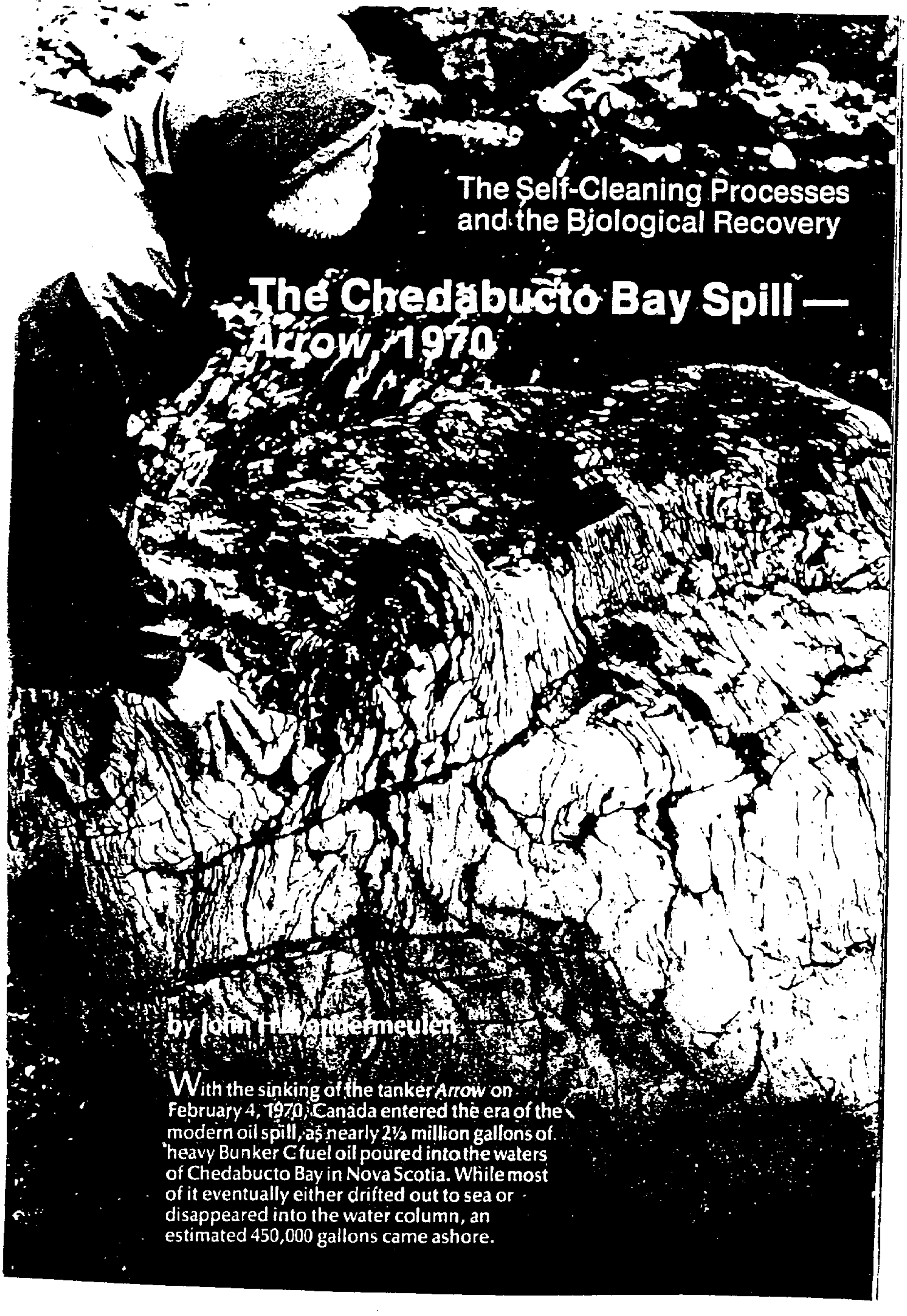

The Self-Cleaning Processes and the Biological Recovery

The Chedabucto Bay Spill — *Arrow*, 1970

by John H. Vandermeulen

With the sinking of the tanker *Arrow* on February 4, 1970, Canada entered the era of the modern oil spill, as nearly 2½ million gallons of heavy Bunker C fuel oil poured into the waters of Chedabucto Bay in Nova Scotia. While most of it eventually either drifted out to sea or disappeared into the water column, an estimated 450,000 gallons came ashore.

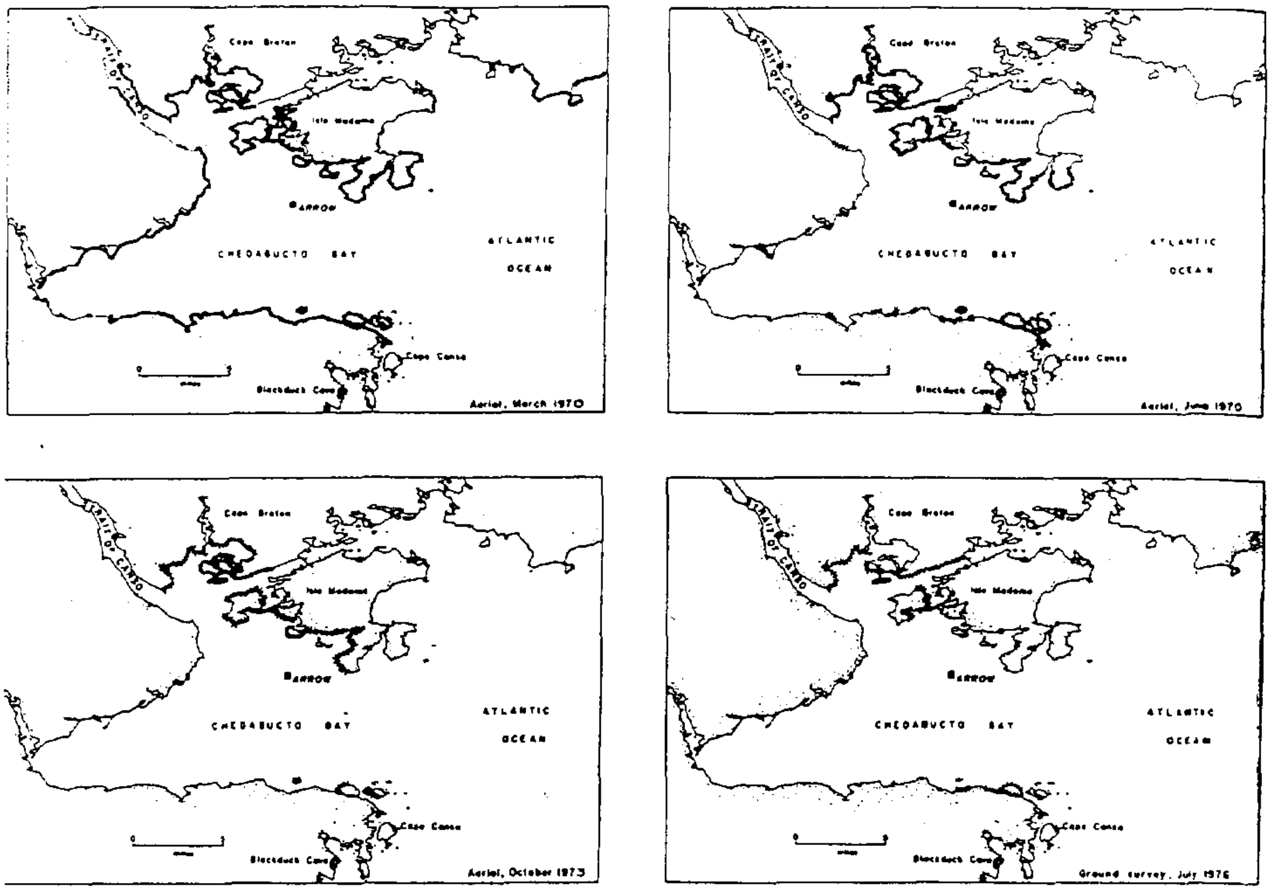

Figure 1. Distribution of oil residues in the shore zone of Chedabucto Bay, determined by aerial inspection in 1970 and 1973 (Owens and Rashid, 1976), and by ground survey in 1976.

Today, nearly eight years after the *Arrow* disaster and despite a massive Task Force clean-up effort by the Canadian government, there are still considerable amounts of the fuel oil in some isolated areas, while traces remain in others. These traces remain despite seven years of changing seasons and heavy weathering.

One of the most frequently asked questions about oil spills is: "Just what is the damage from a spill?" To the scientist, this question poses an enormous problem — one that is relatively new, having come to the fore only in the late 1960s. And with this new problem comes the attendant demand for new scientific techniques. The more we investigate oil pollution, the more complex it becomes.

A multi-faceted follow-up study of the *Arrow* spill was initiated about four years ago at the Bedford Institute of Oceanography in Canada, in collaboration with colleagues at the University of New Brunswick and at Bowdoin College in Maine. We measured and are still measuring not only the Bunker C petroleum hydrocarbons still resident on and in the shoreline sediments, but also the rates of hydrocarbon movement between water column and sediment, the degradation rates, and the tissue oil load and physiological responses of oiled organisms. Hopefully by analyzing the data in their entirety, we can arrive at a preliminary evaluation of the self-cleaning potential on an oiled marine environment. And by knowing rates or half-lives of oil erosion and biological recovery in oiled communities, we may then identify their more sensitive and vulnerable components.

Natural Erosion Patterns: 1970-1976

Oil, once stranded on shorelines, is vulnerable to erosion by various mechanisms — mechanical (wave action or bulldozer), evaporative, chemical (photodecomposition), or biological (bacteria).

Gross self-cleaning of the oiled Chedabucto Bay shorelines is shown in Figure 1. Of the 200 or so kilometers visibly oiled in

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Photograph preceding page shows that while the scum of spilled oil in Chedabucto Bay soon disappeared under the forces of wave action and scouring, traces of weathered and aged Bunker C fuel oil persisted for several years, especially when out of reach of the tide. (Photo R. Belanger, BIO)

March of 1970, about a third were clear of obvious oil cover three months later, partly due to the Task Force clean-up efforts (concentrated mainly in urban or recreational areas) and partly due to natural cleaning by wave action. By June 1970, much of the exposed rocky high-wave energy shorelines of the south shore and of the northeast corner of the bay on and around Point Michaud were clear of visible stranded Bunker C oil.

By 1973, the oil cover was further reduced to a largely patchy distribution, restricted to the low-energy lagoons and estuaries of Isle Madame and Inhabitants Bay on the north shore of the bay. By 1976, six years after the spill, a shore survey found only traces of stranded oil. The high-energy rocky shorelines were largely cleansed of visible stranded oil, and only traces could be found in the low-energy areas of the north shore, on Isle Madame, and Janvrin Island. One exception, Blackduck Cove on the south shore of the bay, remains heavily oiled to this day. It was contaminated in 1970 by a single chance slick that broke off from the main body of oil that was heading out to sea. Today much of the shoreline cobble there remains covered in a heavy asphalt.

The general impression, however, is that most of the stranded oil has now disappeared (Figure 2). Self-cleaning occurred remarkably quickly during the first two years after the spill with 75 percent of the heavily oiled shoreline cleansed by 1973. Although 15 percent of the shoreline was still oiled in 1976, today less than 5 percent remains visibly oiled. An estimate of one and a half to two years for a self-cleaning or erosion half-life* of stranded Bunker C in this particular environment then seems reasonable, although this may be a conservative figure because the half-life of the remaining oil may be much higher.

Wave Energy Cleaning Study

A detailed study of the self-cleaning process of wave energy was carried out by Dr. Martin Thomas of the University of New Brunswick. Immediately after the *Arrow* spill he established his study sites on three heavily oiled beaches, revisiting them annually. These represented three different wave-energy situations — high energy (Crichton Island), medium energy (Arichat Church bluff), and low energy (Janvrin Lagoon).

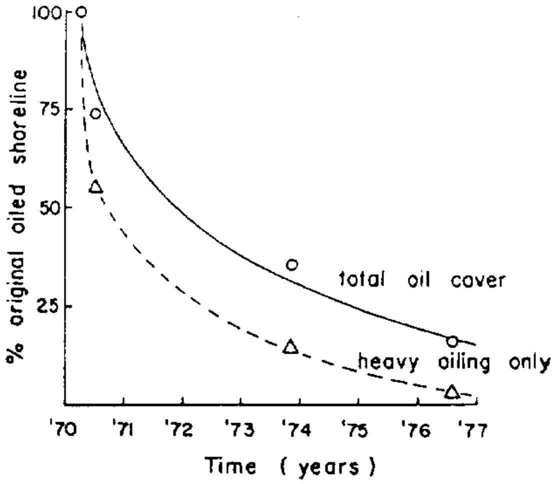

Figure 2. Erosion pattern of stranded Arrow *Bunker C on Chedabucto Bay shorelines: 1970-1976.*

His findings have shown that self-cleaning of stranded Bunker C can be directly related to the amount of wave energy impinging on the shoreline (Figure 3). Thus the rate of self-cleaning on high-energy Crichton Island (Exposure Index 200**) is significantly higher than on a low-energy shoreline, such as Janvrin Lagoon (E.I. = 0).

Thomas' observations also showed that the relative location of the stranded tar on the beach slope greatly affects its self-cleaning potential. Thus oil stranded halfway up the beach is moved off more rapidly than that lying along the top of the beach. In this respect, the high-water spray zone on high-energy beaches — that boulder and tide-pool area above the high-water line and just out of reach of the spent waves — behaves similarly to a low-energy lagoonal shore in terms of self-cleaning. Tar thrown up into these splash-and-spray zones, even along wave-washed high-energy shorelines, has potentially a long residence time, disappearing very slowly.

Thomas' plots also provide some much needed numbers on self-cleaning rates. In Chedabucto Bay, tar stranded along the mid-water line on high- and medium-energy beaches has a self-cleaning half-life of around

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*The time required for half the hydrocarbon concentration to be degraded.

**An index of shoreline wave exposure, based on wave energy, tidal action, and shore topography (Thomas, 1977).

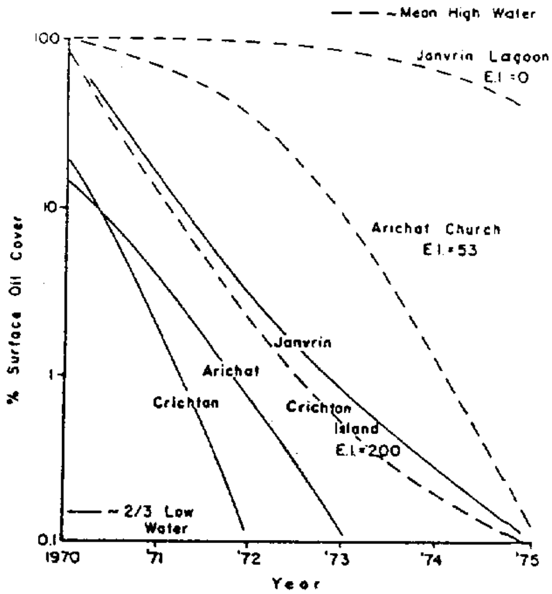

Figure 3. Rates of erosion of stranded Bunker C oil at two tidal levels under different wave-energy regimes. (E.I. is Exposure Index, based on wave energy, tidal flux, and shore topography.) (After Thomas, 1977).

one and a half to two years. However, this half-life is increased by a factor of at least 10 when the Exposure Index drops, such as with the oil stranded on low-energy shores of lagoons and estuaries.

Recovery of Fauna and Flora

The relationship between wave energy and surface oil cleaning is also reflected in the decimation and subsequent recovery of such associated organisms as the kelp *Fucus vesiculosus*, the salt-marsh cordgrass *Spartina alterniflora*, and the soft-shell clam *Mya arenaria*.

Unfortunately, there are no pre-spill data. This is a chief recurring problem in assessing post-spill damage. It is reasonable to assume, however, that the pre-spill populations were probably somewhat similar to those found today in adjacent non-oiled areas. The impact on *Fucus* was immediate and devastating. More than half of the kelp population was destroyed. Recovery did occur, however, but it was and is a relatively slow process. Today's *Fucus* population is not yet equal to the 1970 stock, but recovery is positive. A recovery half-life* estimate of four years is reasonable.

A similar reduction in abundance was observed for the cordgrass *Spartina*, although the recovery pattern differed from that of *Fucus*. Where *Fucus* experienced a gradual and continuous recovery, *Spartina* recovery was not seen until two years *after* the spill. (This underlines the need for caution in post-spill audits. Many effects are not evident until a year or more after the accident.) *Spartina* did recover, however. A reasonable estimate of its recovery half-life is about the three-year mark.

The third indicator organism, the burrowing clam *Mya arenaria*, showed a markedly different recovery pattern. Since 1970, *Mya* has shown a continued decline in abundance, so far with little apparent recovery in sight. Its recovery half-life then appears to be considerably longer than that of either the kelp or the cordgrass, and an estimate of 10 years seems valid.

Erosion Overview

These various observations — the oil cover erosion figures and the biological recovery half-life estimates — lead us to a preliminary model of the total clean-up and recovery potential of this marine ecosystem (Figure 4). We must emphasize here that this is only an approximation. We have left out some mechanisms and have made some guesses. We can, however, make two observations: (1) although stranded oil is a tenacious material, its self-cleaning potential is surprisingly high, with more than 50 percent disappearing by wave erosion in the first two years after the spill; but (2) assuming that about half of Chedabucto Bay shoreline is high-energy and the rest half medium- and half low-energy, then about one-sixth or around 15 percent of the original 450,000 gallons of Bunker C

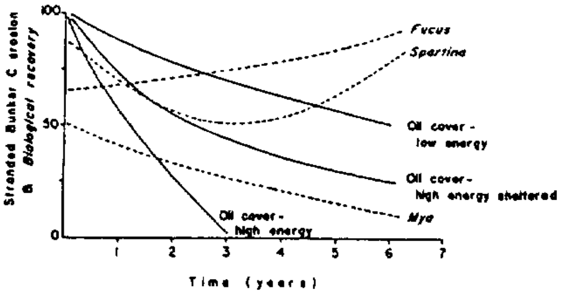

Figure 4. Summary of self-cleaning and biological recovery processes for Chedabucto Bay shore zone, 1970-1976.

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*The time required for a population to reach half its former, non-oiled numbers.

washed ashore is still lying around on low-energy beaches and in sheltered pockets.

Our erosion and recovery half-life estimates, however, draw attention to the continued depression of *Mya arenaria* and the slow self-cleaning of oiled soft lagoonal sediments. Perhaps *Mya* is unusually sensitive, but the fact that it inhabits the soft inshore sediments identifies this clam/sediment system as a potential problem area in environmental recovery. It also makes us aware of the potential long-term impact of a spill, which is generally hidden from view within the sediments.

The Hidden Problem

The stranded Bunker C oil along the top of the low-energy shores is not static, but continually reenters the tidal environment. Only trace amounts, however, enter the tidal water column directly. Instead, the main route of reentry appears to be via the sediments and the interstitial water within the shoreline structure (Figure 5). Judging from flow studies with oiled sediments, the subsequent release of Bunker C hydrocarbons from those oiled sediments back into the overlying water column appears to occur very slowly, about as slowly as that dissolving into the water's edge directly from the stranded tar. The crucial point is that the sediments act as a large sink, and that oil entrapped within these sediments has an extremely high residence time.

Data from our flow studies suggest that, assuming linear loss, approximately 170 years would be required to completely flush out by water flow alone the tar contained in one of our experimental setups. Naturally, this is an over-estimate because we did not include other environmental erosion mechanisms, both physical and biological, but it does demonstrate that leaching of oil from sediments can occur very slowly indeed. For our preliminary model, the erosion half-life for total sediment-bound Bunker C is somewhere in excess of 25 years and possibly longer.

Just what is the composition of the sediment-bound Bunker C—or is it Bunker C? Sediment samples from a chronically oiled beach in a Chedabucto Bay lagoon, one with a tar layer along the top of the beach slope, were taken from the low-, mid-, and high-water line. They were obtained at three depths, 5, 10, and 15 centimeters below the surface, so that we would have an understanding of the changes in the oil's composition within the three-dimensional structure of the beach. The aliphatic or straight-portion chain of this sediment-bound Bunker C was found to be significantly reduced (Figure 6). The gas chromatography (GC)* spectra of all samples, regardless of depth or beach level, showed a marked erosion of the n-alkanes (n stands for normal or straight-chain) up to carbon-30 throughout the entire top 15 centimeters of the beach.

Six years after the Arrow spill of 1970, tarry accretions of weathered Bunker C, pebbles, and beach debris still coat the shore of Blackduck Cove in Chedabucto Bay, Nova Scotia. (Photo R. Belanger, BIO)

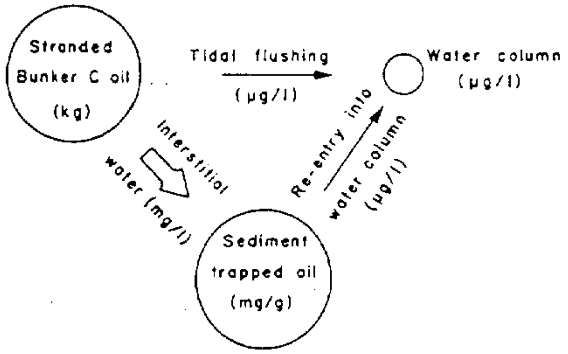

Figure 5. Summary of stranded Bunker C fuel oil reentry pattern into marine environment (Vandermeulen and Gordon, 1976).

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*Gas chromatography is an analytical technique whereby individual compounds in a complex mixture can be separated and identified. Each peak in a GC spectrum represents a separate compound.

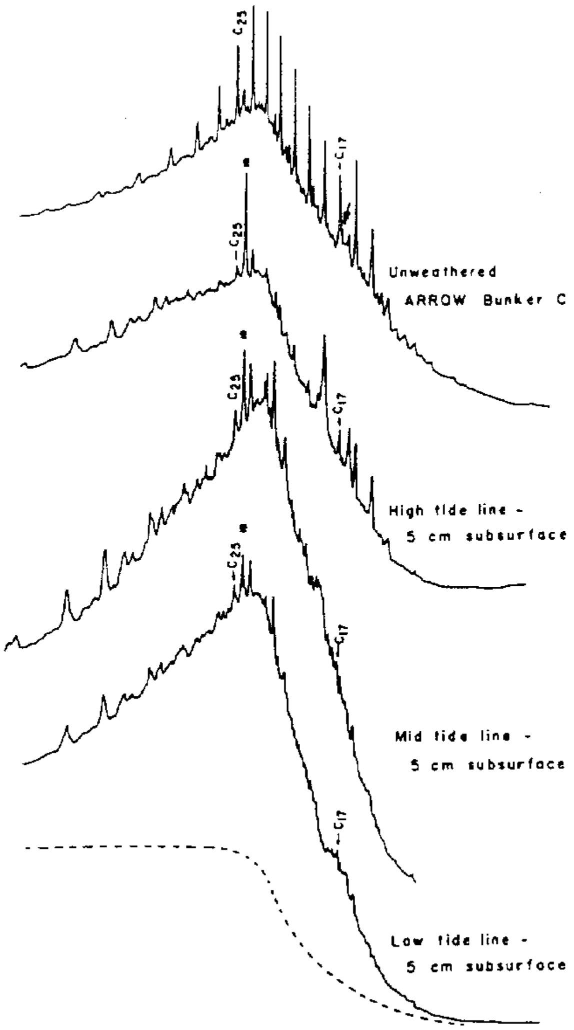

Figure 6. Gas chromatograms of oiled sediment samples (5-centimeter subsurface) from Moussiliers Passage, Chedabucto Bay, N.S. The peaks marked with an asterisk are contaminants, probably of organic or biological origin. The pristane peak is indicated by the large arrow.

The unresolved envelope,* however, suggests there is a considerable amount of undegraded material. Also, the aromatic or cyclic fraction does not appear to differ greatly from that of the *Arrow's* Bunker C, as indicated by the similarities of the fluorescence synchronous** spectra. Thus the aliphatic part of the stranded oil is being degraded preferentially (probably through microbial activity), while the aromatic and multi-ring components of the oil remain, resisting degradation.

This introduces the interesting notion of thinking of the beach and shoreline sediments as the n-alkane filter systems in oiled communities, with characteristic efficiencies and rates. The effectiveness of these "filters" can be estimated from data obtained from a salt marsh on the Quebec-New Brunswick border, oiled with Bunker C in 1974. Two years after this spill, the aliphatic part of the oil that had penetrated into the marsh sediments was significantly eroded, despite continuous replenishment from surface oil. However, as in the Chedabucto Bay beach system, the aromatic fraction remained, apparently unchanged. Thus an estimate of two years for the erosion half-life of n-alkanes in natural sediments does not seem excessive. The erosion half-life for the aromatic component, however, seems to be of much longer duration, possibly as much as 10 years. This brings us to the biologist s concern over the remaining aromatic petroleum hydrocarbons. The oil found in 1977 sediments in Chedabucto Bay, in fact, is *not* the same oil spilled there in February 1970. We are now dealing not with Bunker C, but with an aromatic derivative — one highly enriched with aromatic compounds, with a long half-life, with a long residence time, with a largely unknown composition, and with potential long-term biological implications.

The Biological Implications

Our recent work with Dr. E.S. Gilfillan of Bowdoin College, Maine, has shown that even six years after the *Arrow* spill clam populations in chronically oiled sediments are greatly reduced in numbers, have an altered age distribution, and in many cases show a curious break in the six-year age class, which coincides with the 1970 spill (Figure 7). Tissue growth rates of oiled clams were lower than those of non-oiled sediments. Also, shell growth (that is, the rate at which the growth rings were laid down) after 1970 was less than in those taken from non-oiled sediments (Table 1). Of particular interest was the observation that the clam's efficiency in utilizing food intake (that is, the balance between the amount of carbon

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*The unresolved envelope is the large area under the "hump" of the GC spectrum. It represents a complex mixture of compounds not separated and identifiable as individual peaks by the techniques used.

**A plot of fluorescence emission intensity versus excitation wavelength, during which the excitation wavelength is scanned from 220 nanometers (nm) to 500 nm, while simultaneously scanning the emission wavelength, but always at 23 nm above the excitation wavelength. This technique was adapted from forensic analytical methods involving automobile oils and grease in criminal investigation.

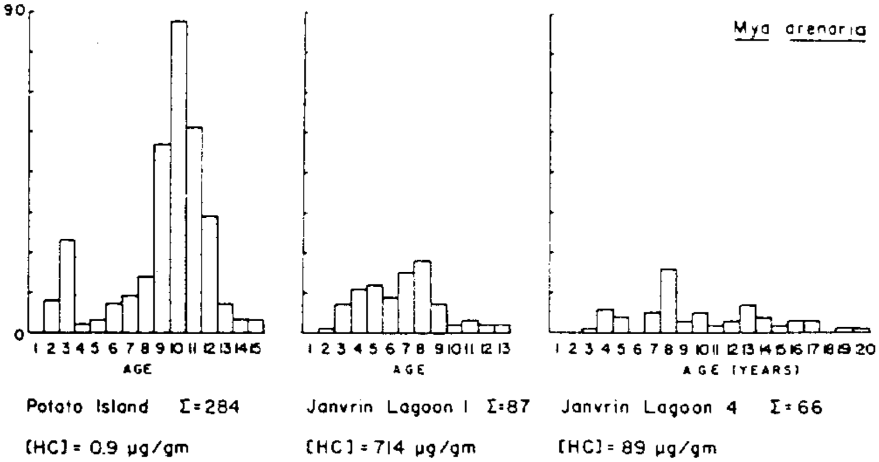

Figure 7. Abundance and population structure of the soft-shell clam Mya arenaria *from a non-oiled (Potato Island) and an oiled (Janvrin Lagoon) lagoon on Isle Madame, Chedabucto Bay, N.S. Abundance numbers are per 0.3 square meters sampling area. Sediment hydrocarbon concentrations were determined by fluorescence.*

taken in versus that amount assimilated and/or respired) differed sharply between oiled and non-oiled clams. In *Mya arenaria* from chronically oiled Janvrin Lagoon this efficiency was very much reduced, and in some batches the clams could be said to be barely holding their own, precariously balancing their carbon budget in their struggle for survival (Table 2).

Thus the *Mya arenaria* population in these chronically oiled sediments is under a great deal of stress. It is down in numbers, the physiology is upset, and the recruitment effort may be impaired.

Aryl Hydrocarbon Hydroxylase

Clams from oiled sediments invariably show petroleum hydrocarbons in their tissues, sometimes in surprisingly high concentrations. Presumably the hydrocarbons are taken up while feeding on sediment and food particles and possibly also directly through the gill membranes. The mechanism of this uptake is not understood as yet. However, once into the tissues we become more concerned with how to rid them of these molecules, which are after all foreign molecules. The time pattern of this depuration or cleansing process in non-oiled seawater is shown in Figure 8. Surprisingly, when clams from oiled sediments were transferred to oil-free seawater, we found that even after 75 days some specimens retained as much as 40 percent of their initial hydrocarbon load within their tissues. In other words, with this slow a depuration rate in non-oiled seawater, the clam's cleansing effort is probably negligible when living in continuously oiled sediments.

Table 1: Shell growth in *Mya arenaria* during the four-year post-spill period as against percentage of growth during four-year pre-spill period.*

Area	% Growth
Non-oiled:	
Control 1 + 2	69%
3	51
4	55
Chedabucto Bay:	
Janvrin Lagoon 1	43
2	42
3	36
4	58
5	33
6	34

***Shell growth determined as a millimeter per year on individual growth rings of 11- and 12-year-old clams.**

Table 2: Carbon budget for *Mya arenaria* from a non-oiled lagoon (Potato Island) and a chronically oiled lagoon (Janvrin Lagoon). Data expressed as micrograms of carbon per hour per 100 milligrams of tissue.

Area	Net C*	Resp. C*	C Flux*
Potato Island	33.22	27.22	+ 6.00
Janvrin Lagoon – 1	23.3	30.43	– 7.13
–2	14.33	26.1	–11.81
–3	6.37	30.95	–25.6
–4	7.66	24.80	–17.15
–5	2.27	23.03	–20.76
–6	2.74	44.6	–41.87

*Data relative, and based on 1,000 micrograms of carbon per liter algal food.

Why such a slow depuration rate? In vertebrates, such as man and other mammals and in fishes, aromatic hydrocarbons are handled by a multi-functional enzyme system termed the aryl hydrocarbon hydroxylase

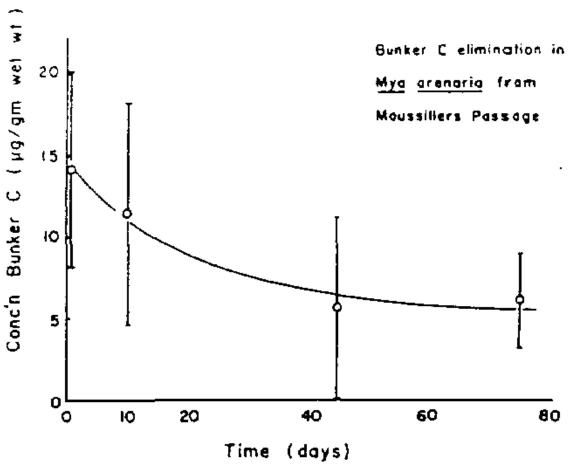

Figure 8. Depuration of Mya arenaria *from an oiled sediment in Chedabucto Bay, transferred to non-oiled seawater. Tissue hydrocarbons expressed as micrograms of Bunker C per gram wet weight of tissue.*

(AHH) system. Normally, this rids the body of unwanted steroids and other compounds naturally produced in the tissues, but when the body encounters a foreign molecule sufficiently similar to the steroids, then this enzyme will handle it as well. In fact, one can enhance the activity of this enzyme system by feeding it larger amounts of aromatic hydrocarbons. Indeed, trout taken from polluted waters show chronically enhanced activity levels of this enzyme.

In collaboration with Dr. W.R. Penrose of the Newfoundland Biological Station, we analyzed clams, mussels, and oysters for this AHH enzyme system. We then attempted to elicit enhancement or "induction" of this AHH activity by rearing the bivalves in experimentally oiled waters. Whereas trout under these conditions showed the necessary basal enzyme response, as well as the induced response, we were unable to detect any such enzyme system in the various bivalves (Table 3). More importantly, we were unable to find this system in clams and mussels taken from the six-year chronically oiled sediments in Chedabucto Bay.

The implication is that in the field the bivalves lack the enzyme mechanism necessary to deal with the long-term aromatic enrichment of the sediments. This is reflected by the slow and incomplete depuration of oiled bivalves when transferred to clean seawater. Indeed, the absence of this enzyme system, which in other organisms metabolizes the aromatic hydrocarbons, may well be the primary cause of all the population and physiological problems that the soft-shell clam experiences in these oiled lagoons.

The Short- and Long-Term Concerns

Self-cleaning of a Bunker C spill appears to be a two-stage process — one short-term, one long. The short-term stage has a half-life of about two years, and appears to be a direct function of wave energy.

The long-term stage has a half-life in excess of ten or twenty years. It is probably largely a function of microbial erosion and is associated with low-energy environments (lagoons and estuaries). Most importantly, this stage involves a compositional change from a Bunker C fuel oil to an aromatically enriched oil.

Biological recovery from shore spill damage is closely linked to the self-cleaning

Table 3: Aryl hydrocarbon hydroxylase (AHH) activity, as determined by benzo[a]pyrene hydroxylation in non-oiled, experimentally-oiled and chronically-oiled (Chedabucto Bay) bivalve molluscs. Activity expressed as fluorescence units per milligram of protein.

Test organism	Treatment	No.	AHH activity[1] x ±S.E.
Brook trout	control	5	0.23±0.23
	4-day, Kuwait crude	5	21.50±8.06
	4-day, Bunker C	5	54.28±41.37
Mya arenaria	control	5	0
	4-day, Kuwait crude	5	0
	4-day, Bunker C	5	0
	chronically-oiled	5	0
Mytilus edulis	control	5	0
	chronically-oiled	5	0
Ostrea edulis	control	5	0
	4-day, Kuwait crude	5	0
	4-day, Bunker C	5	0

[1] Nebert and Gelboin, 1968. *J.B.C.* 243(23): 6242-9.

Aged weathered Bunker C fuel oil literally paralyzed this boulder beach after the Arrow disaster. Such immobilization severely reduces the shock-absorbing capacity of beaches during the winter season. (Photo R. Belanger, BIO)

pattern. In areas of rapid cleaning, recovery follows with a half-life of around four years. In areas of slow self-cleaning, biological recovery of affected organisms is correspondingly slower, with a half-life in the decades, apparently tied to the change in oil composition toward aromatic enrichment.

Our long-term biological concern focuses on the long half-lives of aromatic hydrocarbon degradation and of biological recovery, and on the apparent inability of many benthic invertebrates to deal with these residual foreign molecules.

A further concern is that the absence of the aryl hydrocarbon hydroxylase enzyme system in bivalves may indicate a biological stage where accumulated aromatic hydrocarbons can slowly and continuously enter the food chain, or be carried through reproductive stages.

John H. Vandermeulen is a research scientist in environmental physiology at the Bedford Institute of Oceanography in Nova Scotia. He was general chairman of the OIL/ENVIRONMENT-1977 symposium held in October in Halifax, Canada.

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Persistence of METULA Oil in the Strait of Magellan Six and One-Half Years After the Incident

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INTRODUCTION

On 9 August 1974, the supertanker METULA (206 000 dwt) ran aground just west of the First Narrows in the Strait of Magellan, Chile (Fig. 1). Over the next 1.5 months, until refloating on 25 September, a total of 51 500 tons of light Arabian crude and 2000 tons of Bunker C were released. Due to the narrow constrictions of the Strait, much of the oil lost washed onto 65–80 km of adjacent shoreline (Fig. 1). Since essentially no

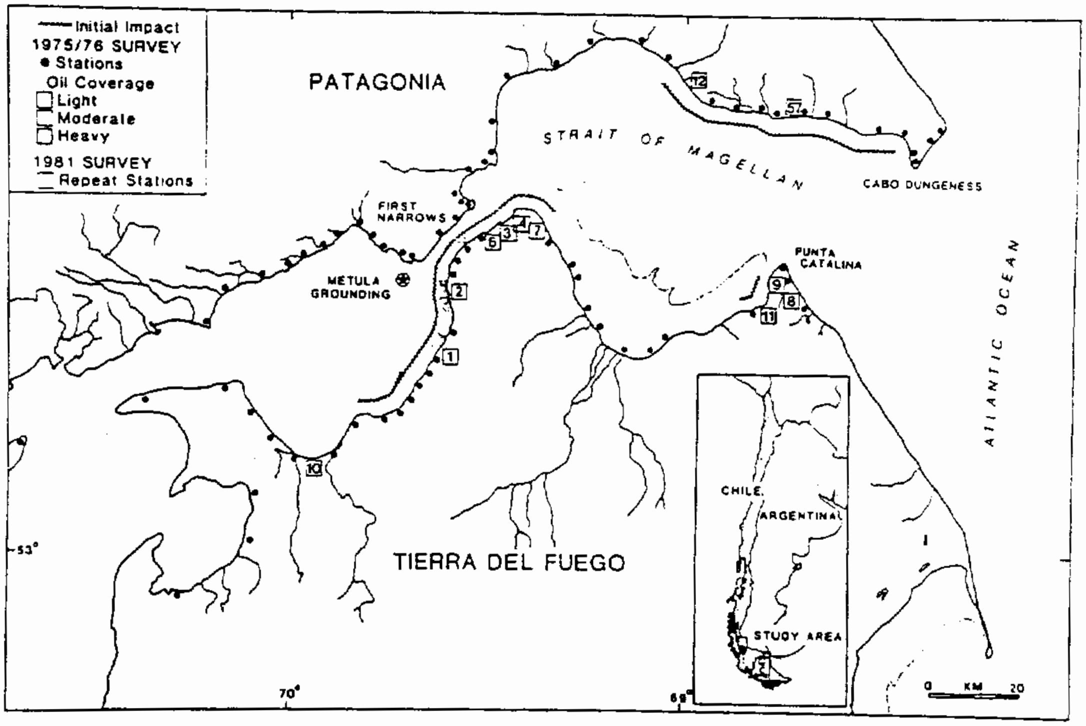

Fig. 1 Location of the METULA oil spill site including station locations, zones of initial impact (August 1974; Hann Jr. 1975), and oil coverage during 1975/76. METULA oil remains most obvious at stations 3, 4 and 6 along the First Narrows.

cleanup occurred, the METULA spill site remains comparable to a large field experiment in which the long-term, natural degradation of spilled oil can be monitored. The purpose of this paper is to describe the distribution of oil remaining along the Strait of Magellan as of February 1981, and to discuss the physical processes that have influenced the oil's degradation over the last 6.5 years.

PREVIOUS WORK

Previous reports on the METULA incident have covered a wide range of topics, including details of the grounding and initial shoreline impacts (Gunnerson and Peter, 1976; Hann Jr, 1974, 1975; Hann Jr and Young, 1979), short-term macrobiological effects (Baker *et al.*, 1976; Straughan, 1978) and short-term microbiological changes (Colewell *et al.*, 1978). Folow-up studies, particularly of a heavily oiled marsh site, were undertaken from one to three years after the spill by the Instituto de la Patagonia, the regional scientific institute of southern Chile. Published reports include effects on macrobenthos (Langley and Lembeye, 1977) vegetation (Pisano, 1976; Dollenz, 1977, 1978) and insects (Lanfranco, 1979). An excellent summary of these and other studies, particularly the effects on birds, is presented by Guzman and Campodonico (1980). Investigations of the physical interaction of oil remaining in particular shoreline environments were undertaken with the senior author one to two years after the spill and form the basis of this comparative study. (Hayes and Gundlach, 1975; Blount, 1978).

REGIONAL SETTING

The climate of the METULA spill site is classified as middle latitude steppe with rainfall averaging 250–350 mm annually (semi-arid). Daily temperatures range from 3°C to 29°C in January, and from −13°C to 9°C in July. The mean annual temperature is 7°C. Shoreline ice is not common.

The shoreline of the eastern Strait of Magellan is influenced by its geologic history and impinging physical processes. By far, the most common shoreline type is composed of mixed sand and gravel reworked from adjacent Pleistocene glacial deposits. There is, however, a very large tidal flat composed of Recent fine-grained sediments located along the south side of the Strait between Punta Catalina and the First Narrows. Tides vary from 6.0 to 10.4 m east of the First Narrows and from 3.0 to 6.0 m within the basin between the First and Second Narrows. Tidal currents reach 8 knots within the Narrows. Strong winds, commonly greater than 50 km/h, blow predominantly from the west (46%). Waves generated between the First and Second Narrows may reach several meters in height. The strong winds, high tides, and swift currents of the area played a major role in the initial distribution of oil spilled by the METULA.

METHODS

This study, undertaken from 18 to 21 February 1981, is based on the resurvey of stations analyzed during August 1975 and February and August 1976 (Hayes and Gundlach, 1975; Blount, 1978). These stations were previously found to contain moderate to heavy concentrations of METULA oil and were considered representative of that shoreline segment. Figure 1 contains the location of all 1975/76 stations as well as those resurveyed during this study.

Comparisons with the data derived during 1975/76 are based on repeat topographic profiling at three sites (where previous reference stakes could be located), and by the analysis of ground-level photographs at seven other sites. At all stations, observations were made of the distribution (length, width, and thickness) of surface oil, and trenches were dug across the beach face to determine the extent of buried, oiled sediment. The physical characteristics (primarily color and consistency) of the remaining oil were noted, and the relationship between substrate (oiled or previously oiled) and resident biological community was given special attention.

RESULTS

Oil spilled by the METULA in 1974 is still found along much of the southern shoreline of the Strait of Magellan. Environments which remain contaminated include exposed and sheltered mixed sand and gravel beaches, exposed and sheltered tidal flats, and sheltered marshes. Observations are summarized in Table 1 and are discussed below by habitat type.

Table 1

Summary of observations at stations revisited during the 1981 survey. Oil was most prevalent at stations 3, 4 and 6—all located along the more sheltered First Narrows

Station number and location	1975/1976 Survey *	1981 Survey
1 Punta Remo	A band of surface oil. 3 m wide, is evident along the upper beach face. Buried, oiled sediment extends under the surface layer for an additional 16 m seaward. Mousse is evident around the bottom edges of many cobbles on the low-tide terrace.	Oil is limited to an oiled-sediment layer, 6.2 m wide, buried 5–20 cm along the upper beach face. The middle to lower beach face and the entire low-tide terrace are free of oil.
2 Punta Baxa	Scattered oily debris is evident along the upper high-tide swash lines. Buried, oiled sediment extends for 12 m along the upper beach face. A layer of asphalted sediment, 35 m wide and 15 cm thick, is located along the upper portions of the low-tide terrace.	METULA oil remains visible as oil-clumped sand along the beach face, and as small scattered patches of oiled-sediment pavement on the low-tide terrace. The lower portion of the low-tide terrace now supports extensive mussel beds.
3 Puerto Espora spit and tidal flat	Very extensive beds of asphalted sediment are located along the interior of the embayment (20–40 m wide) and along the outer, gently sloping beach face (up to 100 m wide).	The interior and exterior zones of asphalted pavement show only minor patchy signs of erosion, particularly along the upper edges.
4 Espora marsh	Consists of a very heavily oiled marsh (18 ha) and a smaller, sheltered tidal flat (3 ha). Marsh plants are dominated by *Salicornia ambigua* and *Suaeda argentinensis*. Almost all flora and fauna within the heavily impacted zone are killed. An additional 23 ha was lightly oiled but killed most of the resident *Suaeda*.	The marsh shows only minor signs of recovery, particularly a 10–30 cm regrowth of *Salicornia* along the upper oiled fringe.
	Along the active mixed sand and gravel beach in front of the marsh, a buried, oiled-sediment layer, 35 cm thick, extends for 16 m along the upper beach face.	Buried, oiled sediment, now composed of hard asphalt, remains present along 2.5 m of the upper berm.
	To the west of this station, a zone of asphalted sediment, 15–20 cm thick and 100 m wide, extends along the upper low-tide terrace.	A zone of asphalted pavement, 90–100 m wide, remains along the upper low-tide terrace.
6 Punta Espora	Tar balls are common along the upper swash lines and oil-stained cobbles appear across much of the beach face. Extensive deposits of asphalted sediment intermittently appear as pockets of clean gravel migrate from west to east along the beach.	Asphalted sediment still remains, having a maximum dimension of 40 m × 5 m and a thickness of 15 cm. No other METULA oil is present; however, some light, oily swashes of recently spilled oil are common along the upper beach face.
7 Cabo Orange	Oil-stained gravel is common along the upper swash lines. An asphalted-sediment pavement, 20 m × 150 m, is present along the upper low-tide terrace.	No surface or buried oil remains along the beach face or low-tide terrace.
8 Punta Catalina	Consists of a washover along the Atlantic coast which has several buried, oiled-sediment layers and a surface of asphalted sediment along the crest of the upper beach face.	This site has been extensively eroded. No oil could be found.
9 Punta Catalina	Small pieces of asphalted sediment are scattered across the upper beach face (located along the west side of the spit).	No oil remains at this site.
10 Southern edge of Bahia Felipe	Pieces of asphalted sediment are present on top of the spit that fronts the area. Behind this spit, narrow discontinuous bands of asphalted sediment line the upper edges of the channel.	No oil remains on the spit; however, the narrow bands of asphalted sediment along the interior margin still persist.
11 Southeast corner of Banco Lomas tidal flat	A discontinuous band of thin oil with scattered tar balls is present along the very upper edge of this huge tidal flat.	Oil remains just as it was previously. A vehicle has driven over the site leaving tracks across the oiled area.
12 Cabo Posesion	Scattered oily debris is found along the upper swash lines.	No oil is present.
57 Punta Daniel	Scattered oil crust is found along upper berm area. Lightly scattered, oiled-sediment conglomerates are on the upper low-tide terrace.	No oil is visible.

*Annual data not available.

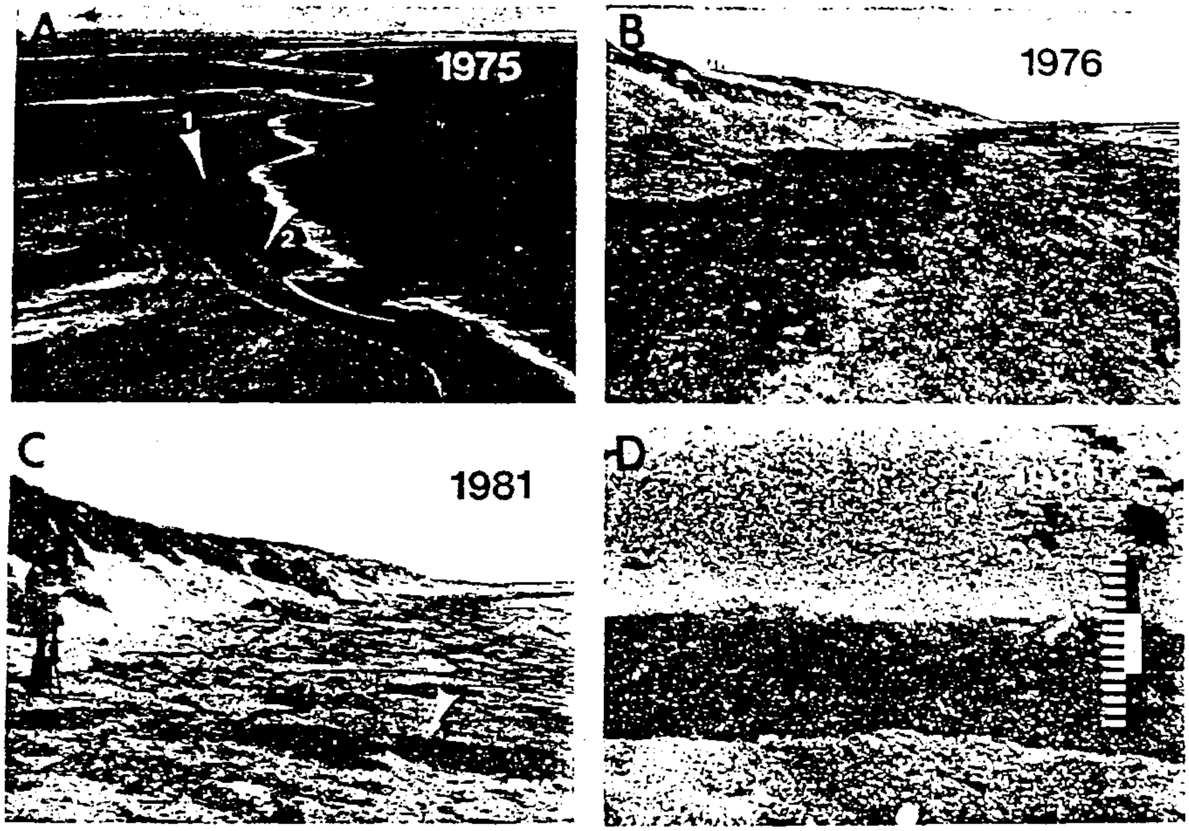

Fig. 2 Photographs of the Punta Remo area (station 1). (A) Aerial view from 18 August 1975. Arrow 1 indicates oil along the upper beach face; arrow 2 points to asphalted sediment along the low-tide terrace. (B) Ground view of station 1 on 9 February 1976. Oiling extended 3 m across the surface and penetrated 5 cm into the sediment. Buried layers of oiled sediment extended an additional 16 m down the beach face. (C) The upper beach face at station 1 on 20 February 1981. No oil is present on the beach face, but oiled sediment remains present 5–20 cm below the surface along a zone 6.2 m wide. Arrow indicates location of Fig. 2D. (D) Close-up of loosely packed, oiled sediment lying below the surface at station 1 (20 February 1981; scale = 30 cm).

MIXED SAND AND GRAVEL BEACHES

Exposed Beaches

The majority of the shoreline impacted by the METULA consists of exposed mixed sand and gravel beaches. during the 1975/76 survey, remaining oil was classified into light, moderate, or heavy coverage (Fig. 1). Lightly oiled areas contained scattered, asphalted-sediment fragments; moderate coverage commonly contained an oiled-sediment pavement at least 1 m wide, while heavy coverage encompassed an oiled zone greater than 3 m wide. By 1981, most areas that had previously been lightly to moderately oiled were clean. Wave activity, causing shoreline erosion (particularly at station 8) or sediment reworking (e.g. stations 7, 9, 12, 57, and the exposed portion of station 10), was the primary cleansing process. Sites that still contained major quantities of oil in 1981 are located at station 1 (Punta Remo) and along the First Narrows (stations 3, 4, and 6).

Station 1 is located along a stable portion of shoreline exposed to waves generated by the westerly winds crossing the embayment between the First and Second Narrows. At the time of the spill in 1974, the entire intertidal zone was covered by thick accumulations of oil. During our first survey in August 1975, one year after the

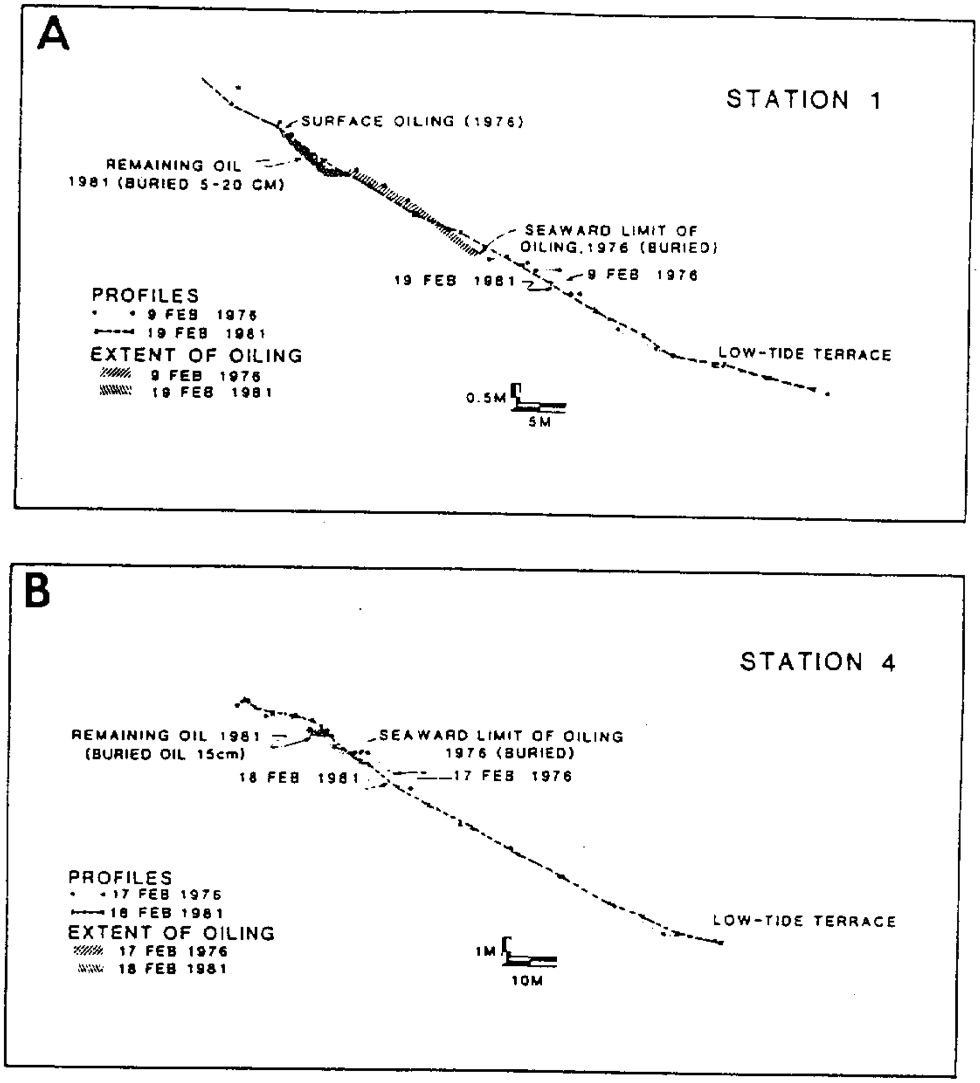

Fig. 3 (A) Comparative profiles (1976 and 1981) of station 1. Surface oil present in 1976 was buried by 1981, so the beach face appears clean. Below the surface, oiled-sediment layers were reduced from 19 m to 6.2 m. Wave action reworked most of the mid beach face sediments and removed the oil from this zone. (B) Comparative profiles (1976 and 1981) of station 4 along the First Narrows. In 1981, rock-hard asphalted sediment remains buried in a 2.5 m zone along the upper beach face. Wave energy is generally low in this area.

spill, oiled sediment remained obvious as a 3 m band along the upper beach face (Fig. 2A, B) and as several buried layers extending another 15 m seaward to the mid beach face. By February 1981, no surface oil was visible; however, a 6.2 m zone of loosely packed, oiled sediment remained 5–20 cm below the surface (Fig. 2C, D). As indicated by the analysis of comparative beach profiles (Fig. 3A), the oiled zone is in the same position along the upper beach face as the original surface layer. Buried oil that previously extended to the mid beach face was reworked and eliminated over the intervening years. In total, the width of the oiled zone was reduced from 19 m to 6.2 m.

The beach at station 4, located along the First Narrows, shows a pattern of oil degradation sim-

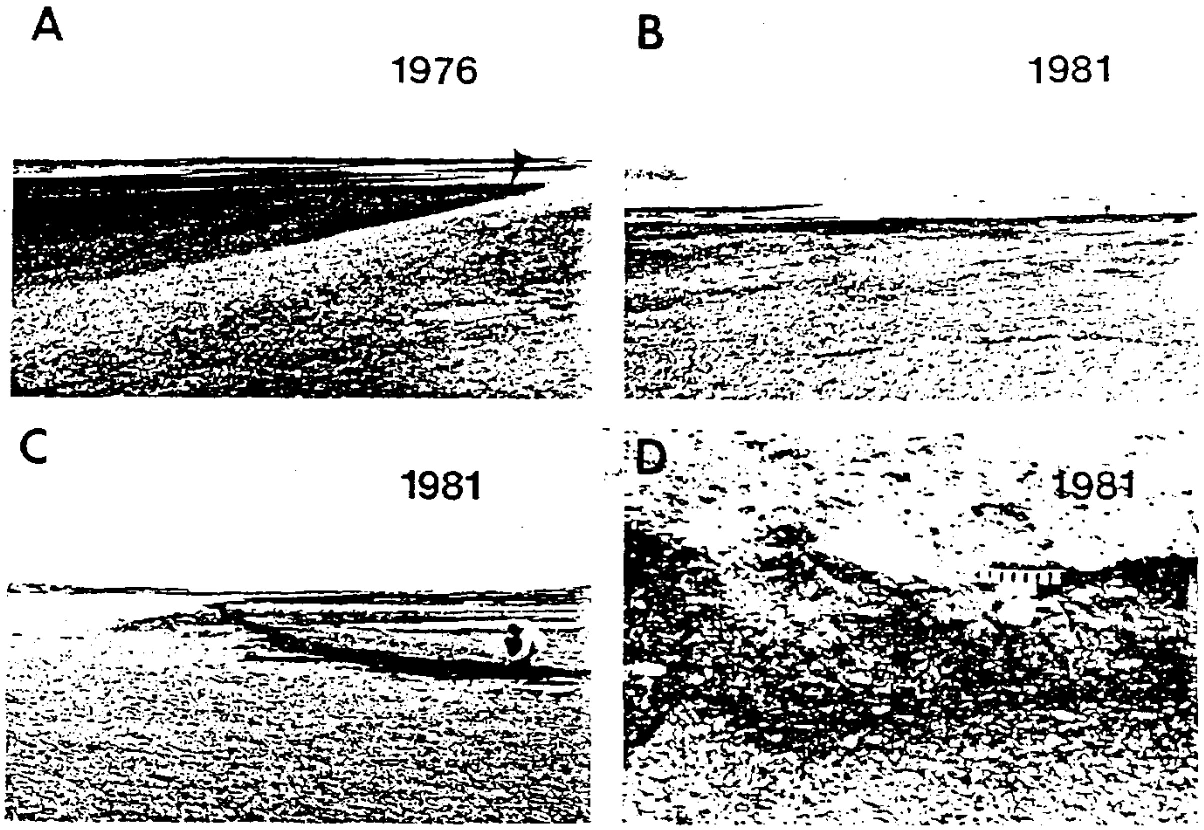

Fig. 4 Views of the asphalted-sediment pavement located along the lower beach face and upper low-tide terrace along the First Narrows. (A) View along the exposed side of Puerto Espora spit (station 3) on 12 February 1976. Arrow indicates the upper boundary of asphalted sediment. (B) Same area as 4A on 20 February 1981. More loose gravel is on the surface of the pavement than in 1976; however, there was little erosion of the pavement. (C) Ground-level view 100 m west of Espora marsh entrance on 20 February 1981. (D) Close-up of the eroding upper edge of the asphalted-sediment pavement on 20 February 1981 (scale = 15 cm). Maximum measured oil concentrations reached ten per cent (Blount, 1978). In many places, brown mousse remains in the center of these thick deposits.

ilar to that of station 1. In this case, oiled sediment was originally buried along the upper 16 m of beach face (Fig. 3B). By 1981, a 2.5 m band of rock-hard asphalted sediment could still be found.

In addition to the beach face, substantial quantities of METULA oil were deposited along the low-tide terrace portion of the shoreline, particularly on the south side of the Strait between the First Narrows and station 1 (Fig. 2A). In 1975/76, oil could still be observed under the cobbles at station 1 and as thick asphalted sediment at stations 2, 3, 4 and 7. The widths of these deposits ranged from 10 m to over 100 m. By 1981, the low-tide terraces at stations 1, 2, and 7 were completely free of oil. Stations 3 and 4, which continued to show extensive terrace oiling, were in the zone of heaviest initial impact. Both stations are located along the south side of the First Narrows—an area of high currents but low wave activity. At each site, the 10–20 cm thick deposits of asphalted sediment had degraded little since 1975 (Fig. 4A–C). In several places, these asphalted-sediment pavements extend to widths of over 100 m. Brown mousse remains visible inside many of the thicker deposits, and gravel is commonly scattered across much of the pavement's surface. The primary area of degradation

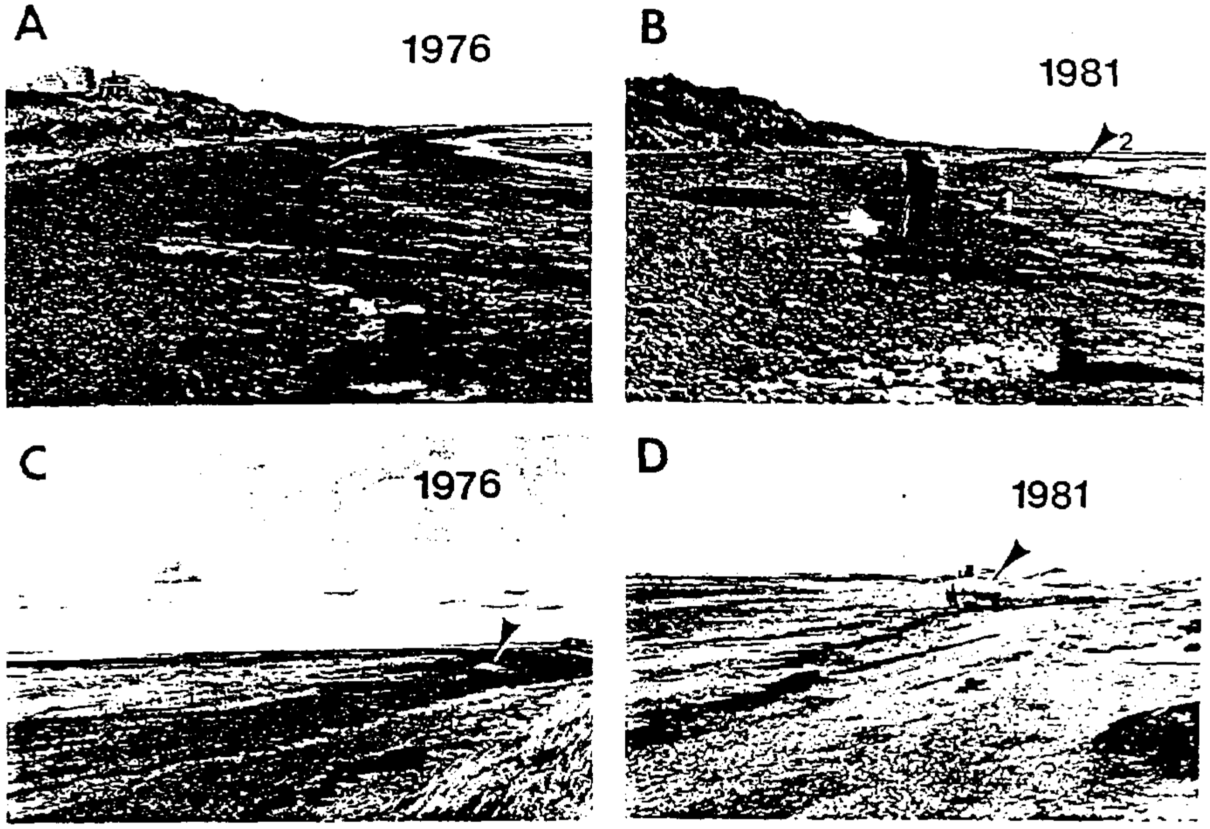

Fig. 5 Ground-level views of asphalted-sediment pavement along the interior, sheltered mixed sand and gravel beach at station 3 at Puerto Espora. (A) View facing west on 16 August 1976. Arrow indicates stake visible in Fig. 5B. (B) West-facing view on 19 February 1981. Arrow 1 marks same stake as Fig. 5A. Only minor erosion of the pavement has occurred over the intervening 4.5 years. There was no physical degradation at all of the oiled-sediment pavement in the southwest corner (arrow 2) of this area. (C) View facing east on 12 February 1975. Arrow indicates block also present in Fig. 5D. (D) Same view as Fig. 5C on 20 February 1981. Only minor erosion has occurred along the upper edge of the asphalted-sediment pavement in this sheltered area.

is located along the most landward edge of the pavement where waves have caused an erosional scarp (Fig. 4D). In some cases, the pavement is undercut which increases the erosion rate.

The biological community varies greatly in this area as it does throughout the Strait region. Patchy but densely populated mussel beds are common along the lowest portion of the intertidal zone. During the spill, there was complete destruction of the biological community where thick accumulations covered these beds; however, the distribution of the marine flora and fauna in the Strait is so patchy as to make extrapolation to all impacted areas impossible. In the First Narrows, extensive mussel beds continue to be present along the lower intertidal zone, and in several areas algae are now attached to gravel on top of the pavement surface. In areas that were heavily impacted and are now free of oil, particularly station 2, there has been a tremendous repopulation of the area by mussels. Long-term biological studies by the Instituto de la Patagonia also indicate an increase in populations over those found after initial impact (Guzman and Campodonico, 1980).

Sheltered Beaches

Almost all the beaches of the spill site are ex-

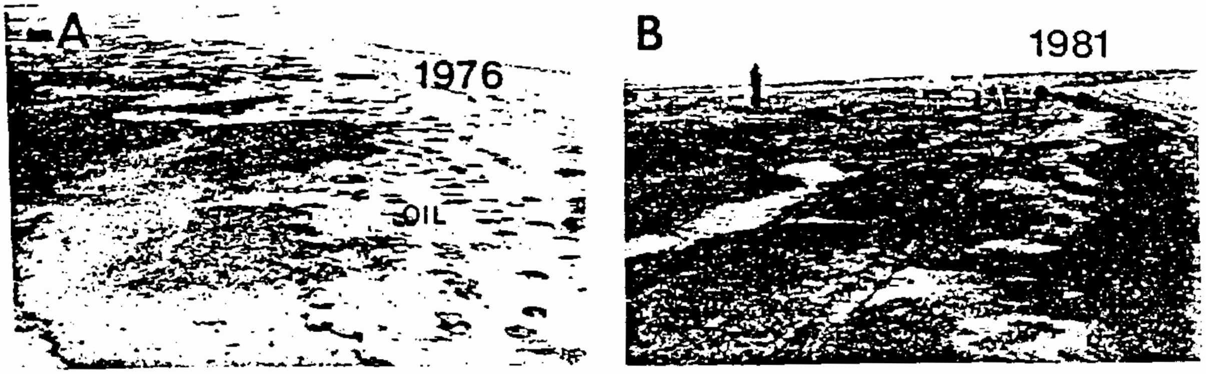

Fig. 6 Views of oil remaining along the upper swash lines of the enormous tidal flat located between Punta Catalina and the First Narrows (station 11) on (A) 16 August 1976 and (B) 18 February 1981. A light, silt crust appears on the surface of the oil. Because this oil was deposited above the zone of wave activity, there has been only minor removal and burial of oil. Oil penetration into the compacted, silt sediment was limited to 2 cm.

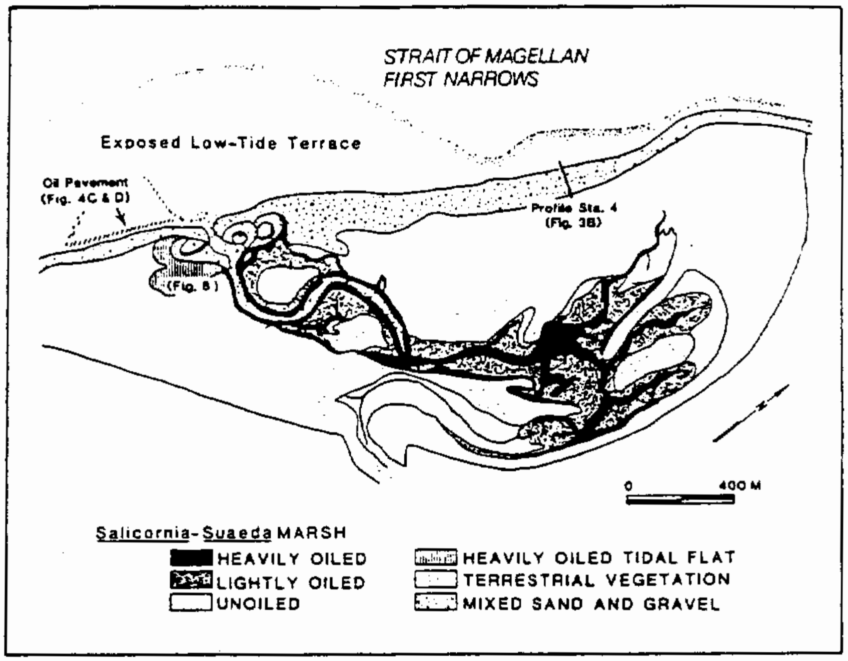

Fig. 7 Plan view of the Espora marsh area indicating the extent of oiling. Figures 8 and 9 contain aerial and ground views of the marsh. In total, 18 ha of marsh and 3 ha of tidal flat remain heavily oiled and totally destroyed. An additional 23 ha were lightly oiled (only *Suaeda* was killed).

posed to waves; however, at stations 3 and 10, a spit shelters the interior beaches of mixed sand and gravel. Station 3, along the First Narrows at Punta Espora, was heavily impacted and serves to illustrate oil interaction within this shoreline type. Because there is very little wave activity behind the spit, there has been almost no change in the overall condition of oil in this area. An asphalted-sediment pavement, 15 cm thick and 20–40 m wide, extends along the entire landward

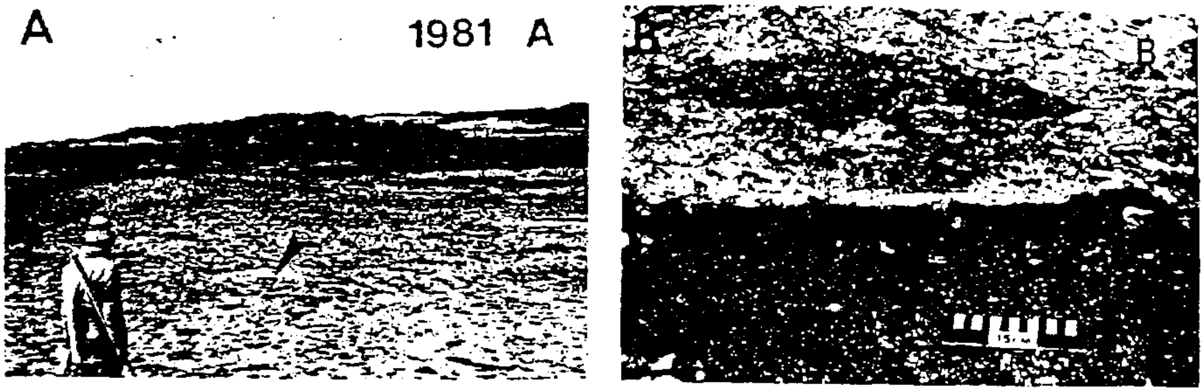

Fig. 8 Ground-level view (A) and close-up (B) of the heavily oiled tidal flat at the entrance to Espora marsh. Arrow indicates location of close-up photograph. Sediment is oiled to a depth of 5 cm.

edge of the embayed area. Differences between 1975/76 and 1981 are limited to some minor erosion along the upper edge of the pavement (Fig. 5A–D). In the more sheltered, southwest corner of this area, there has been virtually no change at all. In fact, the deposited oil still remains very soft and mousse-like in consistency.

TIDAL FLATS

Both exposed and sheltered tidal flats were impacted by oil spilled by the METULA, although major impacts were limited to two relatively small, sheltered tidal flats located along the First Narrows.

Exposed Flats

The south side of the eastern Strait of Magellan contains an enormous tidal flat (10 km × 40 km) composed of fine-grained sand and mud. During the spill, a small amount of oil skimmed over the hard surface of the flat and beached along the spring-tide swash lines in the southeast corner of the area (Fig. 1). Since this oil was deposited above the zone of wave action, it has changed little over the intervening years (Fig. 6A, B). Oil did not sink deep into the sediment due to the impermeable nature of the substrate, but remains only on the upper 2 cm of the flat surface.

Sheltered Flats

The METULA spill site provides two examples of impacted, sheltered tidal flats. One is located behind the Puerto Espora spit on the south side of the First Narrows as discussed under sheltered mixed sand and gravel beaches; the other is at a site called Espora marsh (Fig. 7). The tidal flat located at the entrance to Espora marsh was heavily oiled during the spill. By 1981, there was no indication of recovery. A hard, 5 cm thick, asphalted-sediment pavement covered most of the 3 ha of tidal flat surface (Fig. 8A, B). The presence of a very thin layer of clay on the pavement surface, deposited over the last 6.5 years, illustrates the extremely low rate of sedimentation in the area.

MARSHES

The Espora area also provides an example of a heavily oiled marsh system. During the spill, accumulations were very heavy, primarily concentrated along the channel margins and along the upper edges of the marsh (Figs 7A, 9A). Pools of oil ranged up to 30 cm deep. Dominant vegetation types damaged by the spill were *Salicornia ambigua* (saltwort) and *Suaeda argentinensis* (sea blite). In 18 ha of heavily oiled marsh, almost all vegetation was killed. In the topographically lower central portions of the flat, oil generally floated over the *Salicornia*, but oiled and killed the higher-standing *Suaeda*. This area was considered to be lightly oiled and encompassed 23 ha. A third vegetation type, *Lepidophyllum*, is found above the high water mark and was not greatly affected by the oil. Assuming a 5 cm average depth of oil over all heavily oiled areas, this produces an estimate of 9000 tons of mousse that entered this marsh during the initial phases of the spill.

During the 1981 survey, very little overall recovery of the marsh was noted (Fig. 9B, C).

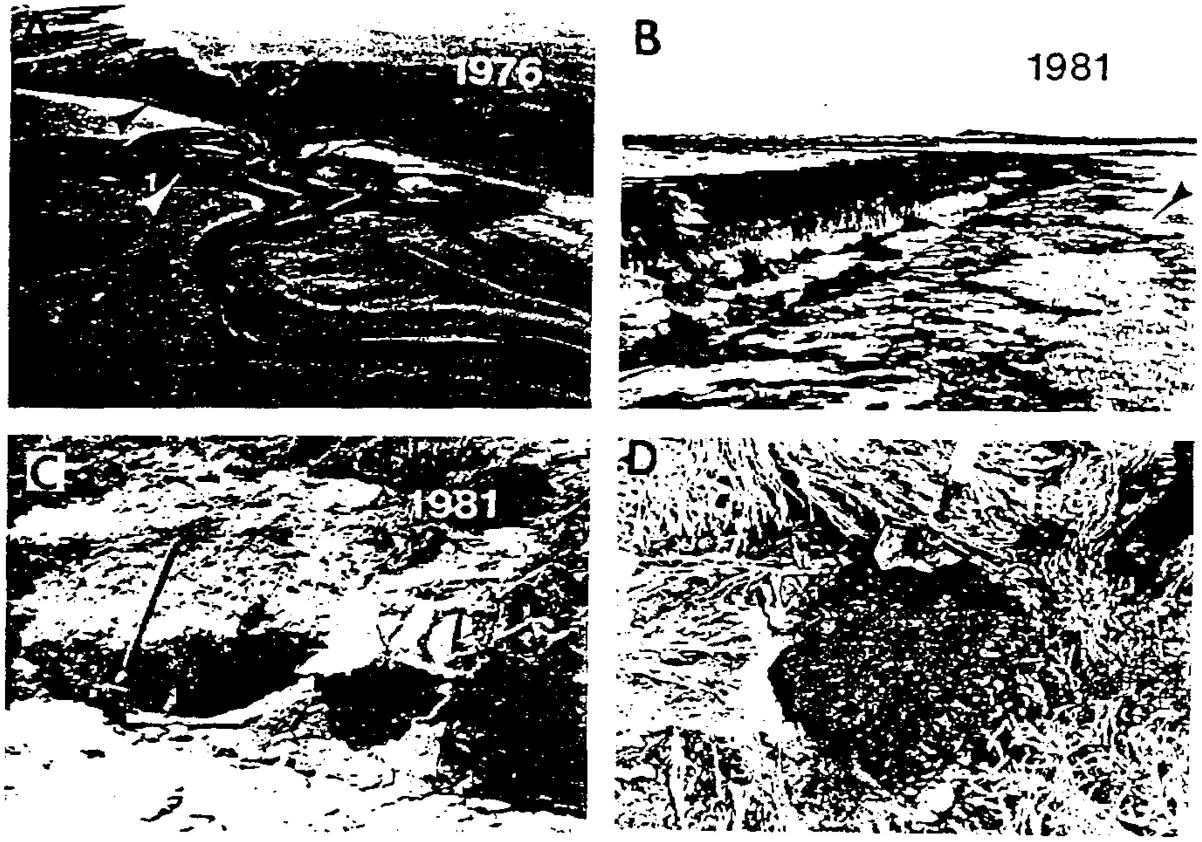

Fig. 9. Views of the heavily oiled marsh at Espora (station 4) along the First Narrows. (A) Overview of the marsh entrance on 9 March 1976. Arrow 1 indicates the location of the oiled tidal flat in Fig. 8. Arrow 2 indicates the asphalted-sediment pavement in Fig. 4C, D. (B) Black and white, infrared photograph of the heavily oiled channel margin on 19 February 1981. Live *Salicornia* is illustrated by arrow. (C) Thick oil coating along channel walls of the marsh. Note that the hardened oil maintains its integrity even though the wall is being undercut. (D) Common view of the remaining oil pools present on the marsh. The color of the oil is black with brown (mousse) streaks.

Heavily oiled channel edges looked as they did previously. In many places, thick mousse deposits of brown color and soft consistency were still evident (Fig. 9D). Only *Salicornia* located along the upper channels showed some 10–30 cm of new lateral growth extending out over the deposited (and still soft) oil. Roots of these new plants, however, did not extend into the oil, but were limited to entry into the dead material above the oil. So, it appears that *Salicornia* at Espora marsh is able to cover the oily surface only when it has a base of previously killed plant material (Fig. 10). The other primary vegetation type, *Suaeda* did not show recovery in the oiled areas. The reasons for the lack of recovery noted at Espora marsh are seemingly related to the thickness of the deposited oil and the lack of degradation processes.

The coating of oil in the marsh area also influences channel morphology. Based on a review of photographs taken in the same area, there has been no increase in the extent of slumping along the smaller marsh channels. It appears that the 0.5 cm thick coating of oil on the channel walls actually inhibits channel collapse. The durability of the oil coating is especially noticeable where sediment has been eroded from under the oil drape, yet the hardened oil coating remains intact (Fig. 9C). This is distinctly different than observed at the heavily oiled, Ile Grande marsh

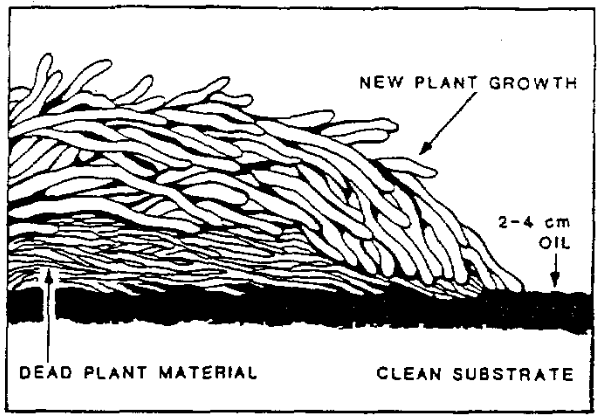

Fig. 10 Illustration of *Salicornia* growth over thick oil deposits. The roots of living *Salicornia* extend only into previously killed plant material and not directly into the oil. The oil in this area is still soft and mousse-like in consistency.

after the AMOCO CADIZ oil spill where extensive channel widening was caused by the loss of living, rooted vegetation to bind the channel wall sediments (Gundlach *et al.*, 1981). Differences are based on the lack of hardened oil along the chanels at Ile Grande.

DISCUSSION

The continued persistence of oil within Strait of Magellan environments necessitates a lengthening of the predicted duration of oil spilled in similar coastal sites. After the 1975/76 surveys, it was felt that oil would remain only two to three years in mixed sand and gravel beaches, and up to 20 years in Espora marsh. Now that almost seven years have passed since the spill and oil remains in many of the previously heavily oiled areas, it is time to increase the predicted duration of spilled oil on low wave-energy, mixed sand and gravel beaches to some 15 years. Where wave action is very limited, as along the First Narrows, persistence may exceed 30 years on this same beach type. Within sheltered tidal flats, there is little reason to believe that oil will ever be physically removed from this environment without complete erosion of the entire site (e.g. channel migration). Similar sentiments can also be expressed for the heavily oiled marsh at Espora. With less than one percent new growth at the site and little evidence of oil weathering, oil may persist for more than 100 years. Even if *Salicornia* overgrows the entire site, oil would still persist just underneath the plants' root structure.

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CHAPTER 26

BIOLOGICAL SURVEY OF INTERTIDAL AREAS IN THE STRAITS OF MAGELLEN IN JANUARY, 1975, FIVE MONTHS AFTER THE METULA OIL SPILL

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Abstract

Field sampling was conducted in areas in the Straits of Magellen that were oiled and unoiled by oil spilled from the tanker Metula in August 1974. Statistical analysis of physical parameters such as beach slope and intertidal height did not show a significant difference between the group of oiled and the group of unoiled sites. However, comparison of the grain size of the oiled and unoiled group of sites showed a statistical difference.

Marsh plants had started to grow through oil in the oiled areas. High levels of petroleum hydrocarbons were recorded in mussels in the oiled areas. The presence of byssus threads alone suggested recent loss of mussels in part of the heavily oiled area.

Biological, physical, and chemical data were analyzed using techniques of ordination, classification, and discrimination. These analyses indicate a negative relationship between the biota and presence of petroleum. While grain size was important in governing the distribution and abundance of species, the visible presence of petroleum was the most significant factor.

The Kuwait crude oil spilled in the Straits of Magellen is similar to that spilled from the Torrey Canyon. In both instances there was large scale mousse formation. It is suggested that it is this physical impact that is the most significant factor and not the cold water conditions.

Key words: Chocolate mousse, Kuwait crude, Metula, mussels, oil in sediments, Straits of Magellen.

Introduction

On August 9, 1974 the Metula grounded at Satellite Patch just west of the First Narrows in the Straits of Magellen. The vessel was not refloated until 25 September, 1974. 50,000 to 56,000 tons of oil were spilled during this period (Hann, 1974, 1975, Baker 1974, Baker, et al., 1975). Most of this was light Arabian crude oil but 3,000 to 4,000 tons of Bunker C were lost during the last few days of the grounding. The light Arabian crude oil spilled was similar to the Kuwait crude oil used as an API reference oil (Warner, 1975) and to that spilled after the *Torrey Canyon* oil spill (Warner, pers. comm.).

In January 1975, at the request of the National Oceanographic and Atmospheric Administration (NOAA), a field survey was conducted in intertidal areas of the Strait of Magellen. Since no detailed background data were available, the sampling program was designed to account for abiotic variables as well as graded amounts of petroleum from the Metula. The abiotic variables studied are those that are known to naturally influence the distribution and abundance of intertidal organisms e.g. intertidal height, grain size of sediment (Straughan and Patterson, 1975), moisture content of sediments. This approach was initiated to eliminate abiotic gradients which may parellel the dosage of oil. Analysis of the data by correlatory techniques should then reveal any significant relationship between species distribution and abundance, and the presence of petroleum.

The distribution of oil in the intertidal zone was documented in August 1974, (Hann, 1974, September-October 1974, Baker, 1974), and January-February 1975, (Baker, et al., 1975, Hann, 1975). Most of the oil was ashore between Punta Remo and Punta Anegado (Fig. 1). The highest concentrations of oil were observed in the Puerto Espora area. Isolated patches of oil were found in high intertidal areas as far east as Bahia San Felipe.

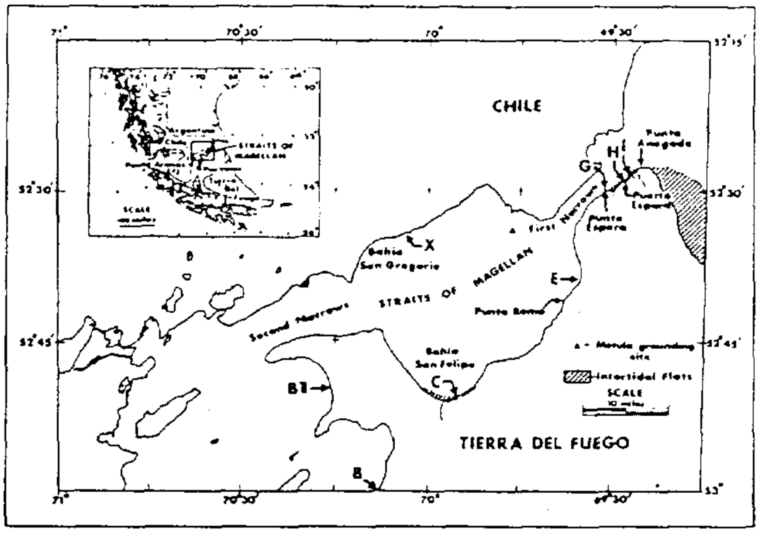

Fig. 26.1. Map of Straits of Magellan to show survey sites. Site A is at Porvenir - see inset.

In January 1975, most forms of oil were still present in at least one of the areas sampled. This included dry oil in patches (Bahia San Felipe), wet chocolate mousse on the surface of sediments, wet chocolate mousse incorporated in sediments, oil/sediment quicksand, brown surface at the waters edge due to presence of oil, buried layers of oil, oil sheen leaching from sediments, layer of wet black oil on sediments, pools of oil, oil sediment mixtures that resemble asphalt paving.

All data are not included herein because this paper is limited in length. A report on this research was submitted to NOAA in 1975 (Gunnerson and Peter, 1976). Since submission of that report, several samples which were believed lost in shipment, were recovered and analyzed. A report containing all data was subsequently prepared Straughan, (1976).

Materials and Methods

Site Selection

Site selection was initially based on the distribution of petroleum reported by (Baker 1974 and Hann, 1974) and later modified by on-site inspection. Four sites (E,G,H,I) were surveyed in the area where oil was initially most heavily deposited and where oil was still visually heavily deposited. Site C was chosen to represent a lightly oiled area. This lightly oiled category assignment was based on Baker's reports and on visual observations of oil in a dry state remaining only in upper intertidal areas. Four sites (A,B,B1,X) were initially selected as possible control areas. Sites B and B1 were visited but were not surveyed. They were areas of large cobbles and were completely dissimilar to any of the oiled sites and were regarded as ecologically unsuitable control sites.

Site A is at Porvenir. While it suffers from the disadvantage of being in an inlet adjacent to a town and thus could be exposed to other sources of man-made pollution, it is similar to some of the oiled sites (e.g., I-5) in that it has both coarse and fine sediments in the lower intertidal areas. Site X, on the northern side of the Straits of Magellen, likewise has mixed intertidal sediments with surface cobbles and intervening sand and gravel.

Sampling Techniques

Quadrats were sampled at each site to account for all visible physical and chemical variables. These included: Intertidal height, Substrate, Presence of Oil, and Presence of Kelp.

Sites I and C both included areas on the open coastline and areas on the edge of a creek draining a marsh. The marsh at Site I was very heavily oiled while that at Site C only had a few scattered patches of oil in the upper intertidal area.

In unstable substrates, namely sediments that are readily mobile and/or less than 3 inches in diameter, the quadrats sampled were 30 feet by 30 feet (≈ 6 x 6 m). Ten points, selected from a table of random numbers, were sampled using a core 3 inches (≈ 7.5 cm) in diameter. Where possible, three cores, 8 inches (20 cms) deep were collected at each of these points. However, much of this area is very coarse and hard and it was impossible to obtain 8 inch cores. The sediments were then sieved through screens (1.5 mm mesh). The organisms were removed from the remaining coarse sediments and preserved in 100% ethanol for later identification. Animals were sorted and stored in 70% ethanol on return to the laboratory. In each quadrat, a sediment sample was collected for grain size analyses and sediment samples were collected for petroleum analysis. The latter samples were collected directly into chemically cleaned 4 oz. aluminum containers provided by Dr. J. Scott Warner, Battelle Columbus, Ohio. Samples were kept cool (air temperatures did not exceed 40°F) until dry ice was obtained. The maximum period between collection and freezing was 2 weeks. Samples were shipped to the United States of America on dry ice and then stored at - 80°C. They were later shipped in dry ice to Dr. J. Scott Warner, Battelle Columbus, Ohio for chemical analysis (Warner, 1975).

In areas of stable substrates, namely large rocks, smaller quadrats (1m square) were surveyed. Subsamples (10 x 10 cms) were recorded and/or collected at ten points selected using a table of random numbers. Samples were only collected if it were not possible to either see and/or identify all species in the field.

All quadrats were related to each other, and, as far as possible to permanent bench marks, by recording intertidal profiles at each site using Emery sticks Emery, (1961).

Species that were not in the areas subsampled but were within either type of quadrat, were recorded. Special attention was paid to either dead or sick animals. Empty shells in good condition were counted. These were separated from old and battered shells in an attempt to obtain a record of recent mortality.

Supplementary samples of the common mussel, Mytilus edulis chiliensis, were collected at both oiled and unoiled sites for chemical analyses of tissues for petroleum hydrocabrons. Animals were placed in chemically cleaned glassware provided by Dr. J. Scott Warner. They were kept as cool as possible in the field (maximum 1 week), frozen in a domestic freezer for 3 days, transported to the United States of America on dry ice, and then stored at-80°C. Prior to shipment to Dr. Warner for chemical analysis, the animals were shucked into chemically cleaned glassware. Care was taken to avoid contamination of the tissues from the outside of the shell. The length of all shells was measured and the total tissue weight in each sample was later weighed by Dr. Warner prior to chemical analysis.

Oiled sediments were washed in acetone to remove the large quantities of petroleum prior to grain size analysis. In most cases, the petroleum was removed after 24 hours of soaking in 6 parts acetone to 1 part sediments. However, two samples were soaked for a second twenty-four hour period. This was necessary because in many instances so much petroleum in the form of 'chocolate mousse' was present, the sediment stuck together in a single mass. However the washing process probably removed some fine grain fractions from oiled samples.

Data Analysis

The Kolmogorov-Smirnov test (Siegel, 1956: 127) was used to determine if the normal physical characteristics (e.g. grain size) of the oiled and non-oiled groups of quadrats were significantly different. This test was chosen because it allowed a comparison between samples of unequal size groups. The error of the chi-square approximation with small samples is always in the 'safe' direction so that if the null hypothesis is rejected, one can view this decision with confidence.

An agglomerative, polythetic method of classification (Williams, 1971) was used to define groups of sites with a similar species' composition. The species were also classified into groups to show similar patterns of occurrences at the sites. Specifically, a Bray-Curtis distance (Bray and Curtis, 1957) was used to quantify the relationships between all pairs of sites (for the site analysis) and all pairs of species (in the species analysis). Flexible sorting strategy (Lance and Williams, 1967) was used to build the dendrograms which display the groups and their hierarchical relationship. Two-way coincidence tables (Stephenson, Williams and Cook, 1972) were employed to show the relationships between the defined site and species groups.

Principle components analysis (Seal, 1964) using the Q matrix form of (Orloci, 1966) and variance-covariance coeffecient was used to analyze the sites according to their abiotic characteristics. Essentially this analysis provides a rank order of sites along the axis created by the analysis to account for the maximum variance in the data.

If the biotic site groups obtained using classificatory techniques coincides with the abiotic site groups obtained by principle components analysis, it would indicate that the species distribution and abundance is related to the abiotic parameters. Spearman Rank Correlation Co-efficients (Siegel, 1956) were calculated to compare the rank order of sites obtained by principle components analysis of the biotic data with that obtained using the abiotic data to test for possible cause and effect relationships.

However, the cause of the biotic grouping or gradients could be one of the less distinctive abiotic gradients which could be overshadowed by a larger but less significant gradient as far as the distribution of these species are concerned. Hence, the data were further analyzed by multiple-discriminant analysis (Smith, 1976). This method is used to study direct relationships between predetermined groups of entities (e.g. the biotic site groups formed by the classificatory analyses) and a given set of attributes or variables measured on or at the entities (e.g. the abiotic parameters of the quadrats).

This method has an advantage over the principal components analysis because the biotic data are directly related to the abiotic data. It has the advantage over the use of single means and standard deviations of individual abiotic parameters because frequently combinations of abiotic variables rather than individual abiotic variables best explain group differences.

Rare species were eliminated from these statistical analyses by considering only species in which more than five individuals were recorded. Algae were not considered in these statistical analyses because species identification is incomplete. Species abundance data were transformed into a relative scale with the largest occurrance equal to 100% and the other occurrances rated as a percentage of this. Petroleum content was determined by the percentage of total carbon tetrachloride organic extractables in the sediments followed by gas chromatography to determine whether there was Metula oil present.

Results

Water temperatures during these surveys ranged from 8 to 10°C while air temperatures averaged 8°C. Ocean salinities ranged from 28 to 31 parts per thousand. The salinity in the estuary at I-4 and I-6 was 30 parts per thousand and the salinity was 18 parts per thousand at C-5.

The intertidal range varied between sites from 22 feet at sites E and G to 6 feet at site A (Table 1). The intertidal range presented here is that recorded at the time of the survey. Hence, the differences are due not only to the difference in tidal range between locations at the First Narrows and those further west, but also to the tides on the actual of the survey.

TABLE 1. Physical Characteristics at Coastal Sites

Site	Intertidal Range (feet)	Profile		Visible Oil						
		Slope	Length (feet)	Kelp	Dry	Wet	Mousse	Seep	Quick Sand	Asphalt
A	6.0	1:32	190							
*C U	10.5	1:10	105		+					
L	2.5	1:426	1,115							
T	13.0	1:94	1,220		+					
E	22.0	1:10	220	+	+	+	+	+	+	
G	22.0	1:10	220	+	+			+		
H	Adjacent and similar to Site I									
*I U	9.0	1:10	90	+	+	+	+			+
L	3.5	1:286	1,000			+	+			
T	12.5	1:87	1,090	+	+	+	+			+
X	15.5	1:19	300	+						

* = Marsh areas excluded.
U = Upper, L = Lower, T = Total.

Sites E and G are both relatively short steep sloping beaches. Both have relatively coarse sediments with a high (more than 50%) percentage of gravel. Gravel is defined as sediment with a diameter of 2 mm or greater.

Sites C and I, in contrast, tend to have some gravel and cobbles in low intertidal areas but they also have finer sediments in these areas. This may take the form of a layer a few inches thick on the coarser sediments or be in the form of discrete patches. This was also observed at A-1 and at site H. The lower intertidal areas at sites C,H,I are long and relatively flat (over 1000 feet wide and with a total elevation of less than 4 feet). The upper intertidal areas at these sites are short and steep with a similar gradient to that found at sites E and G (1:10).

Two sites, G and C, were profiled on two dates a few days apart. There was little overall difference in the profile during that period.

Site X is also a short relatively steep beach (gradient 1:19). It bears more cobble than the other sites but still has gravel, coarse sand, and finer sediments between the cobble.

Kelp was stranded in upper intertidal areas at all sites except sites A and C. However, at sites E and I the kelp was covered in petroleum but it appeared clean of petroleum at site G and had no visible petroleum at site X.

Twelve of the sediment samples that were heavily oiled were washed in acetone 1 to 2 days (Table 2). This means that these samples may have lost finer sediments. Unfortunately there is no way of determining what fraction of the sample was lost. However, Ø sizes as fine as 4.00 were recorded from non-acetone washed samples (5 samples) while the finest Ø size from acetone washed samples was 3.75 (1 sample).

TABLE 2. Characteristics of Sediment Samples

Sample Designation	Acetone Washed (Days)	% Content		Mean Ø (Duplicates)
		Gravel	Sand	
A - 1 No Mud	0	65	35	0.58, 0.71
A - 1 Mud	0	60	40	2.50
A - 2	0	55	45	1.15, 1.77
C - 1	0	20	80	1.15
C - 2	0	65	35	1.51, 1.14
C - 3	0	35	65	0,83, 0.92
C - 4	0	55	45	1.85, 2.12
C - 5	0	30	70	0.65, 0.79
C - 6	0	28	72	0.79, 1.18
C - 7	0	20	80	1.29, 1.30
C - 8	0	22	78	0.98, 1.06
C - 9	0	65	35	1.63, 1.67
E - 2	1	15	85	0.41, 0.28
E - 3	1	66	34	0.19, 0.14
E - 4	1	80	20	0.83, 0.30
E - 5	1	34	66	0.30, 0.12
G - 5	0	92	8	0.22, 0.19
G - 6	0	65	35	0.60, 0.62
G - 7	0	80	20	0.89, 0.83
G - 8	0	30	70	1.28
G - 9	0	0	100	1.35, 1.32
H - 4	1	55	45	0.94, 1.12
I - 1	1	55	45	0.12, 0.35
I - 2	1	70	30	0.43, 0.36
I - 3	1	45	55	0.29, 0.39
I - 4	2	30	70	1.21, 1.12
I - 5	1	80	20	1.36, 1.27
I - 6	2	80	20	0.44, 0.41
X - 3	0	35	65	1.87, 2.30
X - 4	0	35	65	2.20, 2.14

Comparison of similar intertidal areas, for example sites C-1, C-2, C-3, and C-4 which are on a low flat unoiled intertidal area and whose samples were not acetone washed, with samples from sites I-1 and I-5 which were both heavily oiled and acetone washed, showed that the unoiled, non-acetone washed samples contained a slightly lower percentage of gravel (20, 65, 35, and 55% respectively) than the oiled, acetone washed samples (55 and 80% respectively) but that the finest sediments recorded in both areas were within a similar Ø range (3.00 to 4.00). The differences in gravel percentage and Ø size could easily be due to acetone washing but even if they were not, do not suggest a biologically significant change in sediment size between C-1 and C-3 and I-1 and I-5. The mean Ø at these four quadrats from site C fell between the 0.12 level recorded at I-1 and the 1.36 level recorded at I-5 (Table 2). Therefore, it is doubtful that any differences in species composition at these quadrats would be related to different sediment size parameters.

The Kolmogorov-Smirnov test was used to compare the grain size, intertidal height, and beach slope of the group of quadrats that were oiled with the same parameter in the group of quadrats that were not oiled. $X^2 = 1.29$ for beach slope and 0.822 for intertidal height. Neither of these values were significant at 0.01 level. However, $X^2 = 10.04$ for the grain size comparison. This is significant at the 0.01 level for a one-tailed test. This indicates that the grain size of sediment analyzed from the oiled sites was significantly coarser than that analyzed from the unoiled sites. How much, if any of this difference exists in the field, is difficult to determine because the oiled sediment samples were washed with acetone.

At low tide, sand in the upper intertidal areas dried and was blown by the wind. This occurred in all upper intertidal quadrats on the open coastline except at site X where these quadrats were dominated by cobble and in quadrats where the sand was bound by oil. Complete binding by oil was observed at I-2, I-3, E-1, E-2; partial binding by oil was observed at C-8 and E-5; while no binding by oil was observed at C-6, C-7, E-4, G-9, G-8, and G-7. Quadrats below mean water level did not dry sufficiently to blow in the wind. The sand was bound in several ways:

1) by wet oil and/or mousse on or mixed with the sand (E-1, E-2)

2) by a layer of dry oil on top of the sand (C-8, I-3)

3) by an 'asphaltic' formation of sand and oil (I-2)

4) by a quicksand effect (E-2)

Oil was observed seeping out of the sand at G (G-5, G-6) and was also mixed into the water as indicated by the brown waves breaking on the beach at sites E and G.

At one site, site G, oil in the upper intertidal zone was already being eroded away by wave action.

Petroleum was recorded in the sediments at sites C,E,G,H, and I, and not at the two control sites (A,X, Table 3). Petroleum was only recorded both visibly and analytically in two of the quadrats at site C. These data illustrate the patchy distribution of petroleum in the environment unless it is present in massive amounts such as in the main area of the oil spill. The samples from C-5 illustrate this in detail. Sample C-5A was collected from one of a series of a row of dry black deposits of tar at the upper intertidal level of the quadrats; samples C-5B was collected from one of a series of a row of black tar deposits that were brown and wet internally and were fifteen feet closer to the ocean than C-5A; sample C-5C was collected fifteen feet closer to the ocean than C-5B and where there was no visible tar. The tar at C-5B appeared fresher and to have been deposited on a later and lower high tide than at C-5A. The data presented in Table 3 support these observations. Both C-5A and C-5B contained petroleum while C-5C did not contain petroleum. C-5B, the sample with the wet petroleum, had a higher water content (26%) than either the dry petroleum sample (C-5A) (1%) or the sediment sample without any petroleum (C-5C) (3%). Sample C-5C was actually slightly lower intertidally than C-5B and the sediments at C-5C would normally be expected to contain more water than similar sediments at C-5B.

Site C can then be characterized as a site that was initially exposed to a small amount of Metula oil in comparison with Sites E,G,H, and I. Since all of the oil was confined to defined horizontal patches in upper intertidal areas in January 1975, the lower intertidal quadrats were not being re-exposed to this petroleum at the time of the survey and may never have been exposed to this oil. If there were continued re-exposure of lower intertidal areas, one would have expected traces of petroleum in the sediments. The petroleum probably contained lighter and more volatile compounds during the period of initial exposure, so that while the lower intertidal areas may never have been exposed to the Metula oil that stranded, these quadrats could have been exposed to some of the lighter soluble compounds.

At five quadrats, E-1, E-2, I-4, I-5, and I-6, where thick layers of petroleum were present on the sediment surface, two samples were collected - one on the surface and one at a depth of 15 to 20 cms. In all instances there was four to six times more petroleum in the surface samples than in the subsurface samples. This was mainly because the surface sample was more oil than sediment. For example at I-4, I-5, and I-6, the field notes record that the oil was still present in a layer up to 2 inches thick on the surface of the sediment. The high quantity of oil at a depth of 15 to 20 cms indicates that the oil had penetrated much deeper into the sediments.

The petroleum formed "chocolate mousse" - a brown oil and water mixture. The ratio of this mixture can be as high as 20% oil to 80% water Berridge, et al., (1968). Such a mixture has a significant increase in the volume of the spill and can increase the area of exposure to the pollutant.

TABLE 3. Analysis of Sediment Samples from the Metula Oil Spill by J. Scott Warner

Sample Designation	Density[a]	Sediment,[b] %	Water,[c] %	CCl_4 Extractables, % by Given Method		Petroleum,[e] Contamination
				IR	Gravimetric	
A-1 No Mud[d]	2.14	89.3	10.7	0.0024	0.0059	No
A-1 Mud	1.64	58.9	41.1	0.031	0.049	No
A-2[d]	1.84	95.4	4.6	0.0050	0.0046	No
C-1[d]	2.27	89.9	10.1	0.013	0.012	No
C-2[d]	2.17	89.2	10.7	0.063	0.046	No
C-3[d]	1.85	69.4	30.6	0.0230	0.034	No
C-4	2.10	88.6	11.4	0.0010	0.0019	No
C-5A	1.85	93.7	1.4	5.4	4.9	Yes
C-5B	1.53	53.1	26.1	25.4	20.8	Yes
C-5C[d]	1.78	96.9	3.1	0.0003	0.0009	No
C-6	1.76	96.8	3.2	0.0002	0.0010	No
C-7	1.64	95.1	4.9	0.0002	0.0010	No
C-8	1.78	93.4	3.0	4.4	3.6	Yes
C-9[d]	1.76	70.5	29.5	0.010	0.010	No
E-1 Surface	1.59	58.2	32.6	12.3	9.2	Yes
E-1 Below Surface	1.89	92.1	6.3	2.3	1.6	Yes
E-2 Surface	1.96	76.5	16.5	7.3	7.0	Yes
E-2 Below Surface	1.71	93.1	5.9	1.2	1.0	Yes
E-3	1.87	95.6	4.4	0.0037	0.0045	Yes
E-4	1.79	98.7	1.3	0.0027	0.0031	Yes
E-5[d]	1.84	97.0	3.0	0.016	0.017	Yes
G-2[d]	2.02	82.4	17.6	0.020	0.025	Yes
G-3	1.07	14.6	51.5	37.9	33.9	Yes
G-4 Nearby	1.45	91.2	3.1	6.21	5.7	Yes
G-5	1.86	97.1	2.8	0.050	0.044	Yes
G-6	1.93	86.4	13.6	0.046	0.061	Yes
G-7[d]	1.57	96.2	3.7	0.052	0.060	Yes
G-8	1.59	95.6	4.4	0.028	0.026	Yes
G-9	1.54	93.4	6.6	0.015	0.015	Yes
H-1	2.13	84.6	15.4	0.072	0.082	Yes
H-3[d]	1.52	53.9	29.9	18.4	16.2	Yes
H-4	1.96	75.5	24.1	0.31	0.35	Yes
I-1	2.04	80.5	12.7	7.60	6.8	Yes
I-2	1.65	63.4	25.1	13.3	11.5	Yes
I-3 Loose Sand	1.64	97.4	2.0	0.60	0.59	Yes
I-3 Asphaltic Sand	1.83	85.8	8.5	6.2	5.7	Yes
I-4 Surface	1.04	5.8	56.3	44.7	37.9	Yes
I-4 Below Surface	1.95	79.1	14.6	7.3	6.3	Yes
I-5 Surface	1.86	69.5	20.8	11.3	9.7	Yes
I-5 Below Surface	2.16	85.6	10.0	4.9	4.4	Yes
I-6 Surface	0.99	2.6	64.9	36.3	32.5	Yes
I-6 Below Surface	1.99	77.9	14.9	7.6	7.2	Yes
X-1[d]	1.97	93.6	6.4	0.0030	0.0033	No
X-2[d]	2.83	97.2	2.8	0.0037	0.0044	No
X-3[d]	2.04	94.3	5.7	0.0016	0.0032	No
X-4	2.29	83.0	17.0	0.0012	0.0015	No
X-4[d]	2.08	81.6	18.4	0.0027	0.0031	No

a = Density of wet sample as received; b = Extracted with carbon tetrachloride and dried; C = By difference [100- (% sediment + % CCl_4 extractables determined gravimetrically 10^{-1})]. d = The CCl_4 extract contains greater than 5% carbonyl containing compounds as indicated by absorption in the 1750-1650 cm^{-1} range. ● = Assessment is determined by gas chromatographic analysis.

Water in the sediment samples analyzed in Table 3, will be due to several factors. One, of course, is the oil-water content of the mousse. However, intertidal sediments also contain water which will be dependent on the sediment type, intertidal height, and amount of time the sediments have drained between exposure by the tide and collection of sediments. The difference in water content due to sediment type can be best illustrated by two samples from A-1. The water content of the coarse gravel sample was 10.7% and water content in the finer sample was 41.1%. These two samples were collected only two feet apart at the same intertidal level and the same time.

However, in spite of the variations due to factors other than oil, it is obvious that in some instances, namely when thick layers of oil were still present, that these were associated with a high water content. For example, the surface sample at E-1 was light brown fresh appearing mousse. This was in a gravel type of sediment in the upper intertidal area where normally the water content would be low (less than 5%). The water content was 32.6% and it is suggested that the oil:water ratio was in the order of 1:2. At Site I where the oil was darker, the oil water ratio, based on similar assumptions is in the order of 1:1. At site G the ratio varies. Sample G-3 was mainly oil and little sediment so that most of the water was associated with the oil (ratio in the order of 1:1). The high water content at G-2 and G-6 was related to water seepage from the sand in these areas. This seepage contained oil in the form of a sheen. In the other samples, the amount of water appeared related to physical variables other than oil.

Forty-six species of marine invertebrates were recorded on this survey (Table 4). Twenty-eight of these species were polychaetes. This is not a complete species list for the entire Straits of Magellan but a list of the invertebrates found in the study quadrats. Thirty species were recorded in 13 unoiled quadrats (A-1, A-2, C-1, C-2, C-3, C-4, C-6, C-7, C-9, X-1, X-2, X-3, X-4) while 14 species were recorded in 25 oiled quadrats (C-5, C-8, E-1, E-2, E-3, E-4, E-5, G-1, G-2, G-3, G-4, G-5, G-6, G-7, G-8, G-9, H-1, H-2, H-3, I-1, I-2, I-3, I-4, I-5, I-6). Quadrat H-4 was in the edge of a shallow channel that always contained running seawater. Unlike the surrounding black oiled areas, H-4 did not contain visible oil, (Table 5) and it did contain biota that appeared to be healthy. Nearby H-3 contained 16-18% total $C\,Cl_4$ extractables while H-4 contained 0.3% total $C\,Cl_4$ extractables. H-4 contained 15 invertebrate species compared with 5,4, 1 found on H-1, H-2, H-3 respectively. The 26 oiled quadrats contained a total of 25 species.

TABLE 4. List of Living Invertebrates in Quadrats Sampled

CRUSTACEA
- Atyloella sp.
- Edotea tuberculata
- Eurypodius latreillei
- Exosphaeroma gigas
- Halicarcinus planatus
- Macrochiridothea michaelseni
- Serolis
- Valvifera

NEMERTEA

NEMATODA

SIPUNCULOIDEA

INSECTA
- Larvae

MOLLUSCA
- Mytilus edulis chiliensis
- Pareuthria plumbea
- Patinigera magellanica
- Sphenia hatcheri

ANNELIDA
- Oligochaetes
- Arabellidae
- Brania sp.
- Boccardia cf. polybranchia
- Capitellidae
- Ceratocephale crosslandi n.s. sp.
- Chaetozone sp.
- Cirratulidae
- Cirratulis cf. cirratus
- Eteone rubella
- Euzonus fucifera
- Exogone (2 sps.)
- Hauchiella sp.
- Isocirrus sp.
- Lagisca cf. lamillifera
- Langerhansia anops
- Lumbrinereis latreilla
- Lumbrinereis sp.
- Nereis eugeniae
- *Nothria sp.
- Notocirrus chilensis
- Notomastus sp.
- Onuphidae
- Phyllodocidae
- Rhynchospio sp.
- Terebellidae
- Thelepsus setosus
- Travisia cf. gigas
- Typosyllis ?

* This species has been described by F. Piltz in a manuscript sumitted to *J. Linn. Soc.* in 1976.

n.s. sp. = new subspecies.

Comparison of the number of invertebrate species in visibly oiled and visibly unoiled quadrats in January 1975, showed that there were more species in the unoiled than in the oiled quadrats in all instances except site E (Table 5). The two lower intertidal quadrats at site E contained very coarse sand and thus probably never any marine invertebrates. The observations at H-4, where species appear healthy and abundant within a matter of feet of the oiled areas, would suggest that the continued effects on the distribution and abundance of species are possibly related to the physical presence of the mousse in that area and not to continue leaching of soluble components. Likewise, the most abundant Mytilus population was found in H-2, a quadrat with no visible oil but surrounded by visibly oiled areas.

TABLE 5. Number of Living Invertebrate Species in Quadrates With and Without Petroleum Visible, January 1975.

	A	C	E	G	H	I	X
Oiled		0	1	0	6	2	
Not Oiled	9	19	0	7	17		14

The rare occurrences of barnacle scars, a dead crab, and a dead murid would not in themselves be regarded as important. However, the more common dead limpets (Patinigera magellanica), and observations on the mussels Mytilus edulis chiliensis are of importance. Mussels were found attached to rocks at all sites except site E where there were no rocks.

However, all attached M. edulis at site I were dead and some of the attached M. edulis at sites H were dead. At sites I-2 and I-3 there was a stranded layer of mussel shells in good condition suggesting that the animals had died recently. At G-4 there was a zone where mussel byssus threads remained, suggesting that there had been a recent mortality among these mussels.

Analysis of the biological data by classificatory techniques resulted in the formation of seven distinct site groups (Fig. 2). Site group 1 contained sites at which oligochaetes were recorded. The sites were not confined to any section of the intertidal zone. All sites except one (E-1) had no petroleum present. While site group 2 contained sites with oligochaetes at some sites, it is characterized by the presence of Mytilus edulis chiliensis shells. Empty limpet (Patinigera magellanica) shells were also found at some of these quadrats. These shells were all in good condition and showed no signs of deterioration. The quadrats in site group 2 were all heavily oiled.

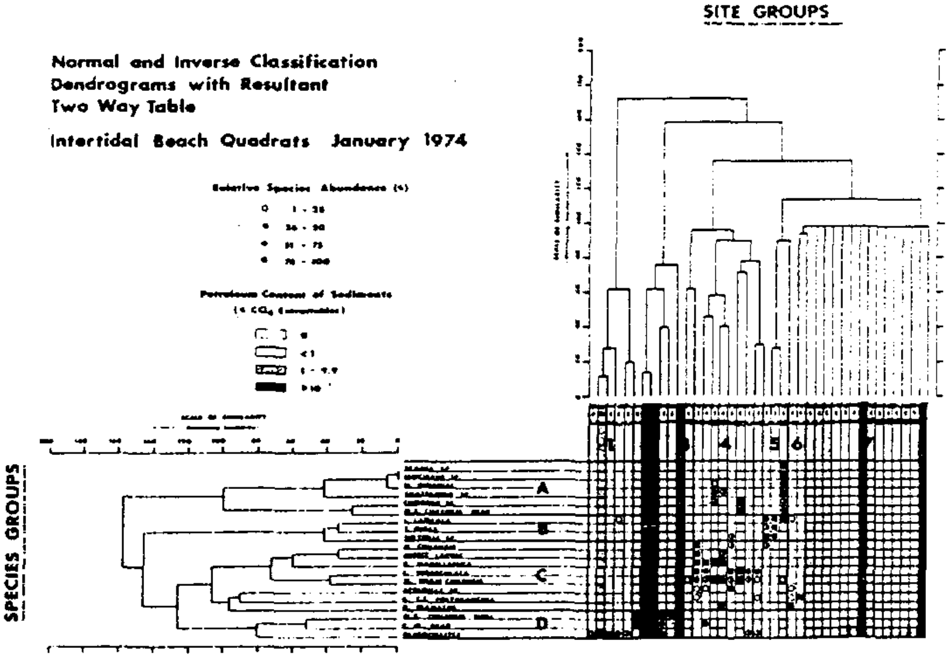

Fig. 26.2 Normal and Inverse Classification Dendrograms with Resultant Two-way Table. Petroleum content of sediments was determined on the basis of % total C Cl_4 extractables and gas chromatography to determine if the Metula oil was present.

Quadrats in site groups 3 and 4 were all in middle or low intertidal areas. All quadrats bore living *M. e. chilensis*. Both quadrats in site group 3 were oiled. No other invertebrates were recorded above the rare species category at these two quadrats. Site group 4 contained both oiled and unoiled sites but all oiled sites were only lightly oiled. Invertebrates in addition to *M. e. chilensis* were recorded in these quadrats.

Site group 5 contained only quadrats found in low intertidal areas. The polychaete, *Lumbrinereis latreilla*, was the dominant species in this group. Both quadrats at site C were not oiled when surveyed while the quadrat at site H was the lightly oiled quadrat in the midst of a heavily oiled area.

Site group 6 contained two quadrats that were not oiled and were dominated by the polychaete *Boccardia* c.f. *polybranchia*.

Site group 7 contained a large number of oiled quadrats in which no animals were collected. There is no consistent trend in intertidal height, beach slope, or sediment size between these sites.

Species groups A,B, and C were found in the middle and low intertidal areas. The oligochaetes, the only living invertebrates in species group D, were not confined to any intertidal level. None of the species groups were restricted to either oiled or unoiled sites. However, two most abundant polychaetes *Nothria* sp. and *Boccardia* c.f. *polybranchia*, and the amphipod, *Atyloella* sp., were not recorded at the oiled quadrats.

Principal components analysis of the abiotic data indicate that intertidal height and visible petroleum are the most important factors, in that order, operating on axis 1 (eigenvalue 1.87, % total variance 37.56) and that total carbon tetrachloride extractables and visible petroleum are the most important factors operating on axis 2 (eigenvalue 1.74, % total variance 34.94) in that order. Slope and grain size are the most important factors on axis 3 (eigenvalue 0.84, % total variance 16.91). Comparison of the rank order along these axis with the rank order of sites obtained by ordination techniques using the biological data and the Spearman Rank Correlation Coefficient revealed no significant correlations.

Multiple-discriminant analysis of the data indicates visible petroleum is the most important abiotic factor (coefficient of separate determination= 40.6). Grain size (coefficient of separate determination = 64.9) is the dominant factor on the second axis and total carbon tetrachloride extractables (coefficient of separate determination = 46.9) is the dominant factor on the third axis (Table 6).

TABLE 6. Coefficients of Separate Determination

Abiotic Attribute	Axis 1	2	3
Intertidal Height	7.2	14.2	13.8
Intertidal Slope	18.5	2.5	29.9
Visible Petroleum	40.6	11.9	2.6
Extractable Organics	17.6	6.4	46.6
Grain Size	16.1	64.9	6.7

The Spearman Rank Correlation Coefficient of - 1.09 indicated a significant ($\alpha = 0.01$) negative correlation between the number of species found in each site group and the mean frequency of visible petroleum. The Spearman Rank Correlation Coefficient was not significant ($\alpha = 0.05$) when the site groups were ranked according to mean frequency of visible petroleum and mean grain size. Therefore these two gradients do not coincide and the negative correlation between species numbers and oil must be regarded as real and not just a coincidental reflection of sediment grain size differences.

Many of the algae collected on this survey await final identification. However, genera such as *Porphyra*, *Ulva*, *Enteromorpha*, *Iridea*, are well represented in the area. Since no data are available in the areas on a pre-spill basis, it is impossible to say how the abundance of the algae compared with that of previous years. Tentatively the collection has been separated into over 20 genera. However, bleached *Porphyra* were observed at H-1, H-2, and I-2. This algae could have been bleached when exposed to high temperatures due to the oil in the area and/or the exposure to high (about 80°F) temperatures the week before the survey. At G-4 *Enteromorpha* was already growing over a thin layer of oil on rocks. However, it was not growing over the mussel byssus threads on the rocks suggesting that the loss of these mussels had occurred only a short time prior to the survey.

Several species of plants were oiled in upper-intertidal areas at sites C and I. The perennial Salicornia ambigua had reshot through the oil at both sites. All oiled specimens at C-5 had shot while 12 out of 32 oiled specimens at I-4 had shot. The specimens at I-4 which had not shot appeared to be dead. The grass, Elymus arenarius, was also oiled. Six oiled plants at I-4 had all shot. The woody plant Lepidophyllum cupressiforme was heavily oiled at Site I. A high percentage of these plants had already sprouted even though at low tide they remained in pools of oil and water about a foot deep.

Table 7 shows the relative size and hydrocarbon content of M. e. chiliensis tissues. Most of the animals collected in the oiled areas were relatively thinner than those from the unoiled areas. This is possibly indicative of stress from the very high concentrations of hydrocarbons recorded (1000 to 5000 ug/g) in the tissues. The background levels from the control sites were in the order of 10 to 15 ug/g.

TABLE 7. Tissue Analysis in Mytilus Edulis Chiliensis

Sample	No. Animals	Wet Weight (g)		Length (mm)			Hydrocarbon (µg/g) Fraction		
		Total	Average	Max.	Min.	Mean	1	2	3
A-1	6	16.6	2.77	54	36	44.1	7	3	1
G-1	9	15.3	1.7	53	36	46.1	940	1100	100
G-3	14	13.0	0.9	49	27	37.3	1600	1300	140
G-4	8	8.0	1.0	46	31	37.0	2700	2000	280
H-2	21	15.2	0.7	42	28	34.1	500	710	110
H-3	5	10.0	2.0	46	34	41.6	490	460	60
X-2	10	15.3	1.5	44	26	36.9	10	5	1

Discussion

The survey of the Straits of Magellan in January 1975, showed that large areas of the intertidal zone were still covered from oil from the Metula oil spill. This is detailed by (Hann, 1975). The present study on the biological effects showed that in the areas most heavily oiled in the First Narrows, there is evidence of continued detrimental effects of the oil spill. These include the changing of sediment characteristics by binding sand that formerly blew in the wind at low tide into an asphaltic type of bed. This will undoubtedly influence the species which will recolonize the area.

Data comparisons on unstable intertidal substrates are generally more difficult than on stable rock intertidal substrates because of the lower number of species in these unstable areas. For example, the infaunal comparison of marsh species only revealed one specimen of a oligochaete species at I-4. This species was also recorded at other oiled and unoiled high intertidal quadrats outside the marshes.

In general, more species are found in lower intertidal than higher intertidal areas (Straughan, 1973, 1975; Straughan and Patterson, 1975, Patterson, 1974). This trend is also found in the Straits of Magellan. Hence, comparison of data on the low intertidal flats at sites C,H and I should provide data that is more readily interpreted than comparison of data from upper intertidal areas. Likewise, comparison of the fauna in the similar marsh quarats reveals little information since only one invertebrate species was recorded.

Comparison of similar quadrats from the low flat intertidal areas at sites C and I revealed little difference in physical parameters but a marked contrast between the number of species in the oiled and unoiled areas. There were no living animals collected in I-1 and I-5 while there were 9,5,6, and 1 species recorded at C-1, C-2, C-3, C-4 respectively. It should be noted that while only one species of tube dwelling polychaete Boccardia, was recorded at C-4, over 500 of the specimens were collected in the quadrat samples.

The physical presence of the oil on and in the sediments appears a very important factor. In other words, any soluble components may not be having a significant effect on the biota after 5 months. This was supported both by visual observations and discriminant analyses. H-4 had no oil visibly present but is surrounded by visibly oiled areas (e.g., H-3). Fifteen species were recorded in H-4 and only one species was recorded in H-3. The number of species in H-4 also belies any suggestion that the sites where the oiled quadrats were located contained fewer organisms prior to the oil spill than the sites where the non-oiled quadrats were located.

The data reveal fewer organisms in the heavily oiled area, large numbers of empty shells in good condition, and evidence that mussel communities were once more extensive. While this does not conclusively demonstrate cause and effect, because the mortalities were recent, because the oil had been present in large amounts for five months, because species distribution and abundance was more closely correlated to the presence of petroleum than natural physical parameters such as sediment grain size, one can only conclude that the continued presence of spilled oil was responsible for reducing the biota.

These findings have been contrasted to those reported by Baker 1974, in the months immediately following the spill. Baker concluded that there was little damage from the oil spill. The present report shows that in the five months after the spill there must have been mortality because the differences cannot be related to physical parameters. The differences between Baker's conclusions and the observations reported herein, are probably partially a result of the age old question, when does one count the dead bodies? Species such as mussels are able to survive adverse conditions for weeks and/or could be counted as living in early surveys but be covered by oil with the shells closed, and really be dead. Other differences such as differences in infauna between the two surveys are related to the differences in the two surveys. Baker surveyed a large number of sites in a month and directed her report to almost the entire ecosystem. In the present survey, the time was shorter but more detailed observations were made on a few specific areas confined to the intertidal zone.

Recovery of the vegetation had commenced in the marsh areas as indicated by the regrowth of plants through the oil. However, this optimistic note must be viewed with caution because studies after the Arrow spill in Canada have shown that maximum mortality in at least one marsh plant, Spartina alterniflora, may be recorded 2 years after the oil spill (Thomas, 1977).

This spill differs from most of the documented large oil spills in several respects:

1) oil was deposited intertidally in the form of chocolate mousse
2) oil remained intertidally for a long period
3) lower, as well as higher intertidal areas, were heavily contaminated by this chocolate mousse for at least 5 months.

It is difficult to compare the suspected mortality with that of other crude oil spills because of the lack of documentation of similar habitats. However, data recorded from unstable areas 6 months after the oil spill in the Santa Barbara Channel did not reveal any effects on the biota from the oil spill (Trask, 1971, Straughan, 1973). Differences between these two crude oil spills include chemical composition of oil, physical behavior of oil, and time of exposure to oil. Sandy beaches in the Santa Barbara Channel were not exposed to prolonged dosages of oil of the magnitude recorded in the Straits of Magellan, and there are no records of the extensive type of mousse formation that occurred in the Straits of Magellan.

The only other large spill of similar oil to the Metula spill, was that from the Torrey Canyon. Kuwait crude oil was spilled in the latter case. (Warner, 1975) reports that the Metula oil is very similar to the API standard Kuwait crude oil. In both cases there was extensive mousse formation. However, the shores of Great Britain were subjected to a rigorous cleanup program which included the use of detergents that are now considered too toxic for general use. The available biological data reports mainly on communities associated with more stable rocky shores in Britain, rather than those less stable substrates found on the south shores of the First Narrows.

It is interesting to compare the oil content of sand examined after the Torrey Canyon with that reported herein. For example, the highest oil content of sand reported by (Smith, 1968) was 11% from very heavily polluted sand at Sennen approximately 3 months after the oil spill. This is considerably lower than the oil content of the most polluted sites in January 1975 (30%-40%). This suggests a lower level of contamination of British than Chilean shore lines.

Therefore, in addition to being one of the largest oil spills to date, the polluted intertidal areas of Chili have been subjected to the longest and highest dosage of this type of crude oil. As the oil has been in a mousse form it has not dried out to even form recolonizable substrates but has remained in a sticky form which is not at all similar to any normal intertidal physical habitat. Exposure to these physical parameters doubtlessly had a significant influence on the biota without even considering the chemical toxicity of the oil.

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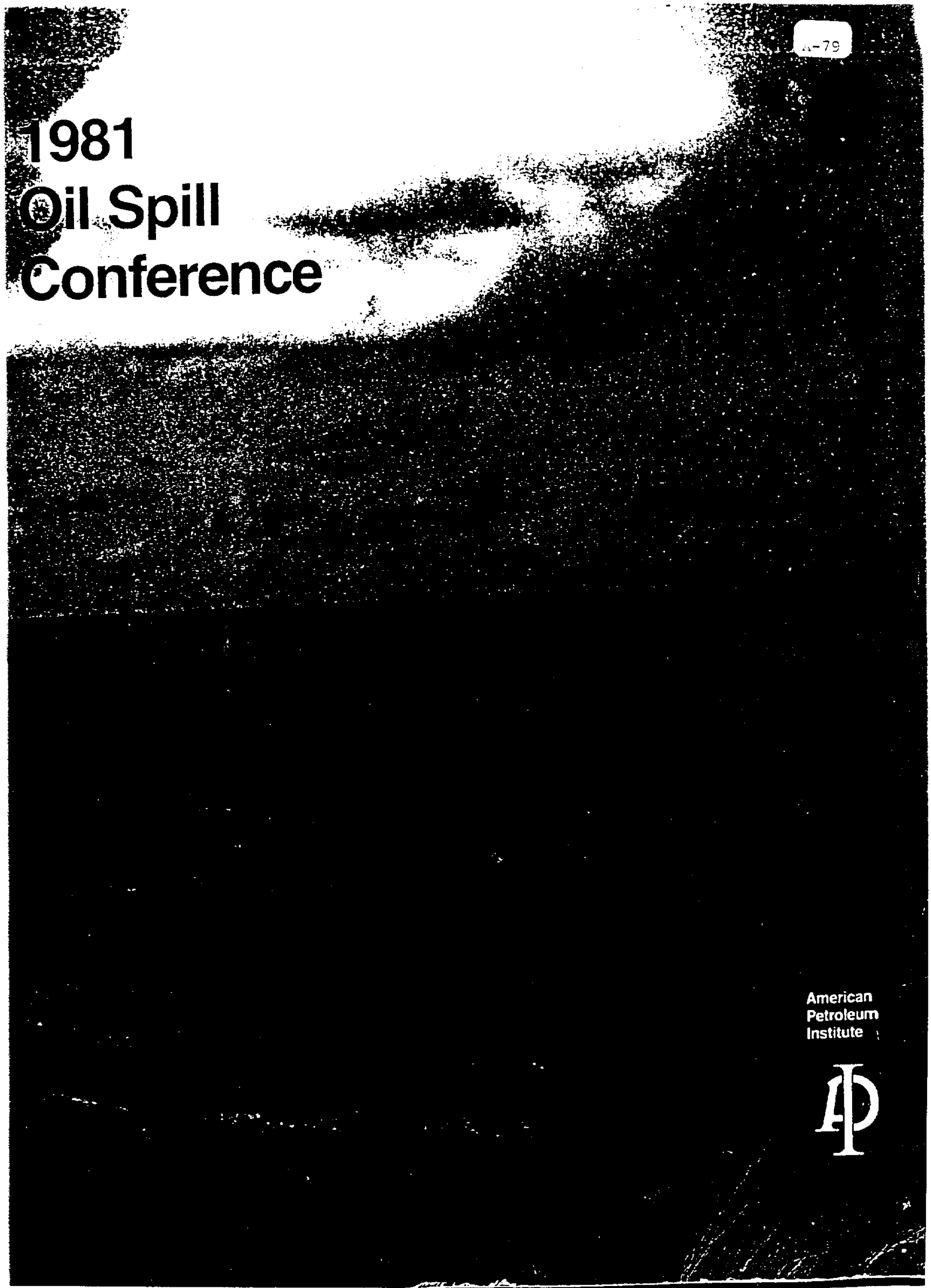

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SHORELINE OIL TWO YEARS AFTER *AMOCO CADIZ*: NEW COMPLICATIONS FROM *TANIO*

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ABSTRACT: *The latest in a series of joint Franco-American surveys of the* Amoco Cadiz *(233,000 tons; March 17, 1978) spill site was conducted during May and June 1980. The purposes of this survey were to determine remaining surface oil, buried oiled sediment, oil incorporation in interstitial water, and recovery of attached macroalgae.*

Oil was found to persist primarily as tar blotches and black staining along exposed rocky shores and as oil-contaminated (indicated by surface sheen), interstitial water in previously heavily oiled, sheltered tidal flats. Less commonly, oil was present as asphalted sediment and oil-coated rocks in sheltered embayments. The cleaned marsh at Ile Grande remained significantly damaged from the oil; however, both upper and lower marsh grasses showed some recovery. At another marsh, no recovery occurred in uncleaned, heavily oiled areas. On sheltered rocky shores, heavily oiled algae showed rapid recolonization by Fucus; *however,* Ascophyllum nodosum*-dominated areas showed less recovery.*

The Tanio *oil spill on March 7, 1980 (7,000 tons lost) impacted 45 percent of the* Amoco Cadiz *spill site and severely complicated further differentiation of* Amoco Cadiz *oil in many areas. In total, 197 kilometers (km) of shoreline were impacted; 45 km were heavily oiled. Nine weeks after initial impact,* Tanio *oil occurred as patches of heavy oil along sheltered and exposed, rocky shores. Sand beaches and tidal flats were generally free of oil. Several hundred soldiers continued to pressure spray dispersants and water to clean up oiled areas, even in high wave energy and isolated localities.*

Introduction

The 2-year study of the *Amoco Cadiz* (233,000 tons of crude oil March 17, 1978) oil spill site in Brittany, France, presents an opportunity to understand the longer term impacts of spilled oil on a variety of temperate shoreline types. The extent of shoreline oiling, resulting from the offshore breakup of the 27,000-dwt tanker *Tanio* during spring 1980, is also discussed because the addition of this new oil along some of the same section of Brittany coast may severely complicate ongoing fate-and-effects studies.

Reports about the *Amoco Cadiz* are numerous and encompass a wide variety of biological, chemical, and geomorphic topics. Hess (1978), Conan et al.(1978), Spooner (1978), and a forthcoming symposium proceedings edited by D'Ozouville and Conan (in press) present the most comprehensive summary of impacts and effects. Papers particularly concerned with the persistence of *Amoco Cadiz* oil are Atlas et al. (in press), Berné and D'Ozouville et al.(1980), Gundlach (1979), and Hayes et al. (1979). Detailed investigation of the *Tanio* was undertaken by Berné (1980).

The climate of Brittany is temperate, moderated by the strong influence of its maritime setting. Low-pressure areas formed in the North Atlantic are responsible for generating strong, westerly winds and high seas. The shoreline is characterized as a low-lying, plateau-shielded coast having large protruding headlands dominated by igneous bedrock, large embayments associated with each headland, and smaller, less common, drowned river valleys (rias). Because of a 6- to 9-meter (m) tidal range, the bottom of each embayment often becomes exposed during low tide, creating a very large surface area that could be oiled. This factor was particularly important in the long-term persistence of oil in sheltered tidal flats. Lastly, tidal currents, strongly prograding from west to east through the English Channel, were extremely important in influencing the overall distribution of shoreline oil.

Methods

Visits to the spill site to determine oil persistence were made during March, April, August, and November 1978; March and November 1979; and May 1980. A total of 147 sites have been established since 2 days after the grounding (Figure 1). Two types of stations were created: (1) rapid survey stations, at which

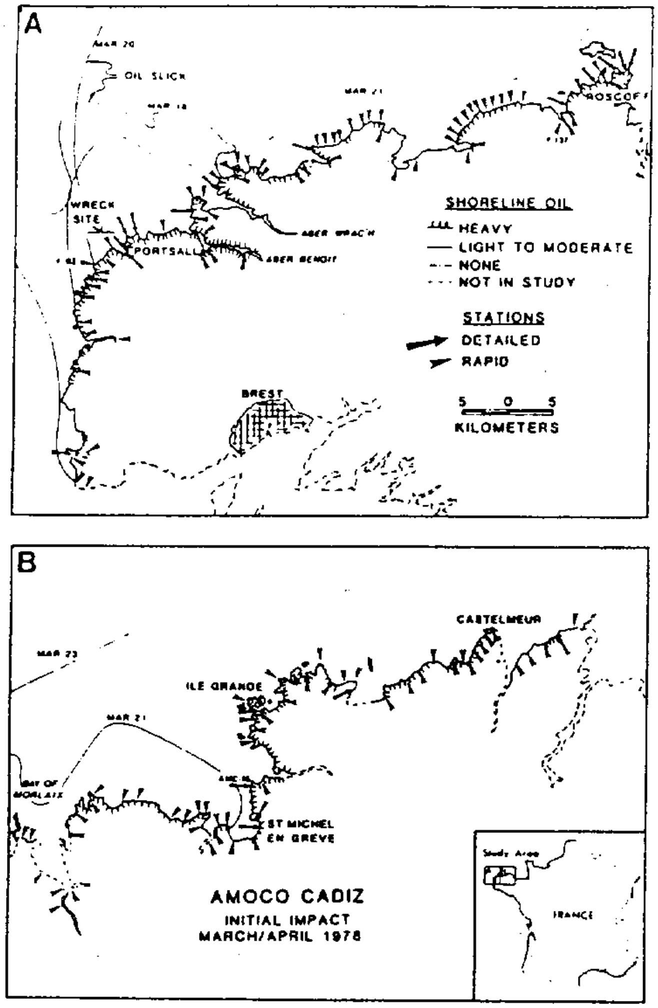

Figure 1. Oil distribution and station locations during initial impact of *Amoco Cadiz* oil (adapted from Berné and D'Ozouville, 1979).

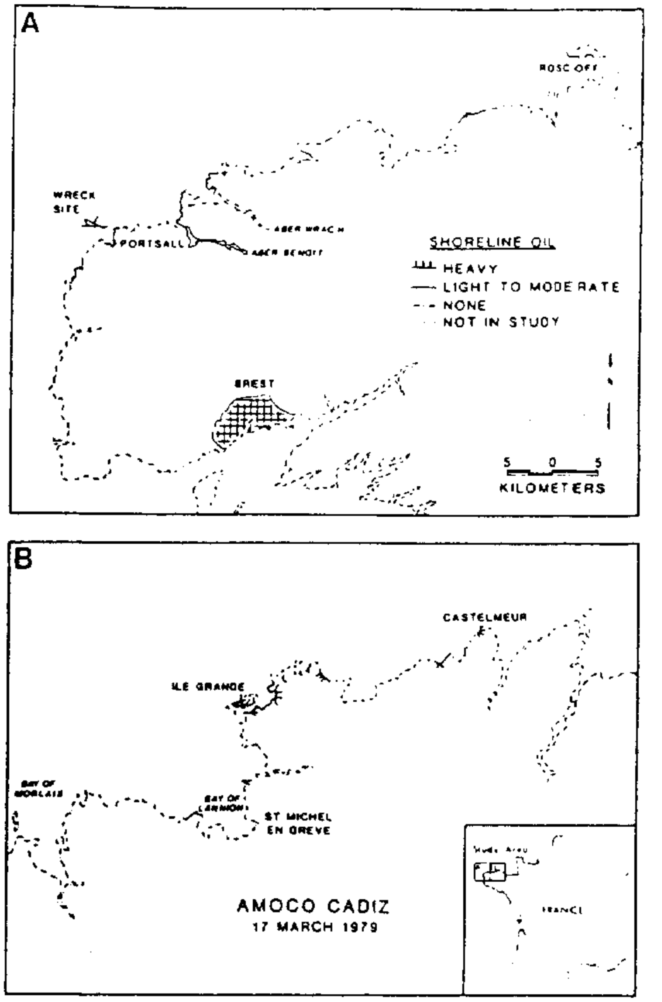

Figure 2. Shoreline oil remaining one after *Amoco Cadiz* wreck. Oil was found most commonly in more sheltered embayments (adapted from Berné and D'Ozouville, 1979).

surface and buried oil concentrations and obvious biological impact were quickly assessed; and (2) detailed study stations, at which surface and subsurface oil content were measured along a topographic beach profile and overall oil distribution was studied in detail. Numerous overflights of the spill site added understanding of initial oil distribution patterns. During the *Tanio* study undertaken from March 20, to April 21, 1980, 56 new stations were added to yield a total of 131 survey sites in this impact zone. Two aerial overflights aided in determining overall oil distribution, especially on offshore islands. Detailed analysis of algal growth, surface area coverage, and zonation were undertaken at four oil-impacted sites in Portsall during June 1979 and June 1980.

Results

Overall changes. Figures 1 and 2 show shoreline distribution of visible *Amoco Cadiz* oil during and one year after the spill. Figure 3 shows the extent of oil spilled by *Tanio*. Changes in surface oil coverage and concentration are tabulated in Table 1. As indicated, it was approximately 62,000 tons (or 26 percent) of the total *Amoco Cadiz* cargo that washed onshore during the first few weeks after the grounding. Within 3 weeks, this content was reduced to 15 percent of this (to less than 10,000 tons) primarily by natural processes. By 1 year after the spill, natural processes had diminished further the extent of shoreline still showing evidence of the spill. It was expected that by April 1980 (2 years after the spill), obvious shoreline oiling would be very limited, but the occurrence of *Tanio* greatly confused the issue.

Persistence of *Amoco Cadiz* oil on particular shoreline types. Because of the great complexity of the Brittany shoreline, initial and followup observations are discussed in terms of specific shoreline types. These environments coincide with those discussed by Hayes et al. (1980) as part of an oil spill Environmental Sensitivity Index (ESI) which ranks shorelines in terms of the potential, long-term persistence of oil. The 2-year study of the *Amoco Cadiz* site provides an opportunity to reconfirm or modify the index accordingly. The ESI is juxtaposed with observations from this study in Table 2. Environments are discussed in order of increasing oil persistence.

Exposed, rocky headlands. As first observed during the *Urquiola* spill, waves reflecting off steep, bedrock headlands kept floating oil from impacting the shore (Gundlach et al., 1978; Figure 4A). Very similar conditions existed during the *Amoco Cadiz* spill, so that these areas generally remained free of oil throughout the spill (Figure 4B).

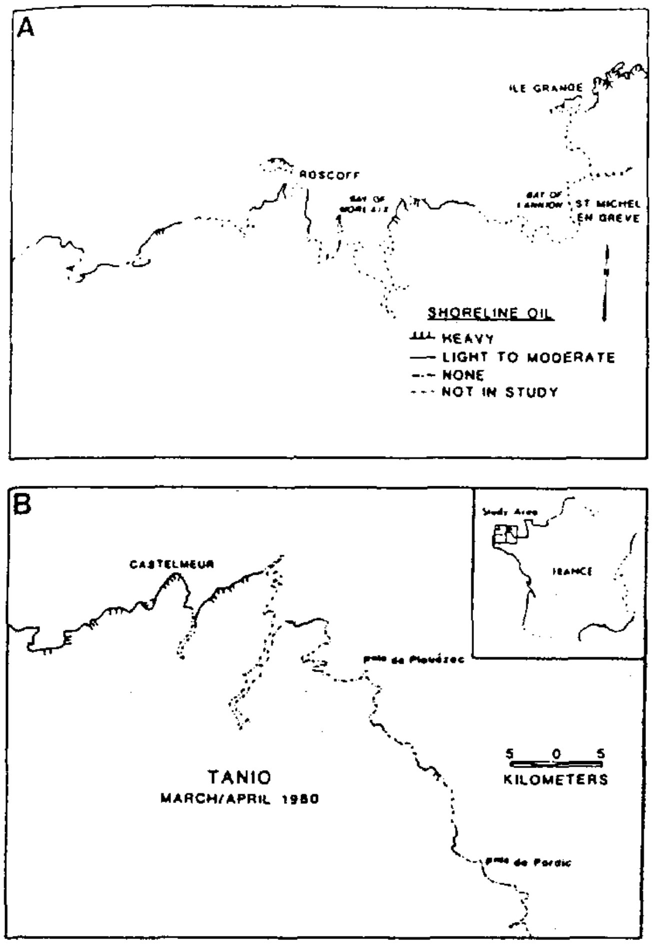

Figure 3. Shoreline impact of *Tanio* oil. Approximately 45 percent of areas previously oiled by *Amoco Cadiz* were reoiled by *Tanio*. Castelmeur and the tourist area called the "rose coast" were most heavily oiled (adapted from Berné, 1980).

Eroding, wave-cut platforms. Unfortunately, most wave-cut platforms were dominated by surface coverage of boulders or sediment, so a clear case of oil on this shoreline type is not available from this study. Where typical, well-defined platforms are present, oiling was not heavy, and high waves and difficulty of access prevented investigation.

Fine-grained sand beaches. Several typical, compact fine-grained sand beaches were present and heavily oiled in the study site (Figure 4C, D). Incoming waves rapidly removed most of the oil; burial was minor and limited to less than 30 centimeters (cm). In areas where wave activity was limited, mechanical cleanup was necessary. By July 1978, only light and scattered oil-sediment layers were evident; 1 year later no oil was visible. In one mechanically cleaned area, substantial erosion was observed 2 years after the spill; however, because of no long-term monitoring studies, natural erosion cannot be separated from that induced by man.

Table 1. Shoreline Pollution Resulting From the *Amoco Cadiz* and *Tanio* Oil Spills (March 1978 to April 1980)

	Heavy, km	State of shoreline oiling, light to moderate, km	Tons present
Amoco Cadiz			
End of March 1978	72	0	62,000
End of April 1978	175	155	10,000
End of May 1978	109	123	(a)
November 1978	54	156	(a)
March 1979	8	69	(a)
Tanio			
April 1980	45	152	6,000

[a] Difficult to determine because oil was thinly scattered along most of the shoreline.

Coarse-grained sand beaches. Less than 1 percent of the Brittany spill site can be characterized as coarse-grained sand beach. In contrast to the long, open sand beaches of the United States (e.g., Cape Cod and Long Island, the beaches in Brittany are small, semisheltered pocket beaches (Figure 4E). During the spill, extensive mechanical cleanup was used to remove heavy oil deposits. No surface oil was visible by July 1978, but several deeply buried, oiled-sediment layers were present. Because oil first impacted the shoreline during an erosional phase of the beach cycle (storm-induced), subsequent deposition of sand during calm weather caused burial of the oil/sand mixture. In fact, 2 years later, since there was no intervening period of similar erosion, oil still was found 84 cm deep at a coarse-grained sand beach near the wreck site (Figure 4F).

Mixed sand and gravel beaches. Models for this shoreline type were based on heavily-oiled, mixed sand and gravel beaches exposed to moderate-to-high wave energy at the *Metula* site (Patagonia, Chile). Such exposed beaches are not common in Brittany where, for the most part, they are located in fairly sheltered embayments fronted by large tidal flats. Oil impact on these beaches varied from light to moderate; there was little mechanical cleanup. Because of relatively low wave energy, the scattered oil formed an asphalt pavement (Figure 5A, B), which was still present 2 years after the spill.

Gravel/boulder beaches. This shoreline type comprises moderately sorted gravel, cobble, and boulder beaches. At least one good example of heavy oil impact on each was observed during the *Amoco Cadiz* spill. The historical sequence of oil persistence on a gravel beach is presented by study of station AMC-16 (see Figure 1 for location). Initial oil impact on the area was very heavy and concentrated along the upper beach face (Figure 5C). As similar deposits from the *Metula* had turned to an asphalt pavement over time, cleaning of the area was attempted, not by removal of oiled gravel, but by pushing it down the beach face into the active swash zone; this was somewhat effective. The quantity of remaining oil was reduced by November 1979, but since there were yet no major storms (generating high waves), oil was present still along the lower beach face. By the time of the next site visit in May 1980, after a particularly stormy winter, no oil remained (Figure 5D).

Station F-82 (south of the wreck site) is illustrative of the behavior of oil on exposed boulder beaches. The area was heavily impacted during April 1978 (Figure 5E) as a result of a wind shift at the beginning of the month. By November 1978, the extent of oiling was reduced substantially (Figure 5F). A year later and after several severe winter storms, only scattered blotches of tar remained. Therefore, residence time for natural degradation of oil in this environment at the *Amoco Cadiz* site was limited to 1 to 1.5 years.

Exposed tidal flats. Tidal flats exposed to moderate- to high-wave energy are present in the following two forms in Brittany: (1) as exposed, low-tide terraces fronting fine-grained sand beaches; and (2) as wide (several kilometers) sand deposits located in depositional embayments. Oil had little impact on

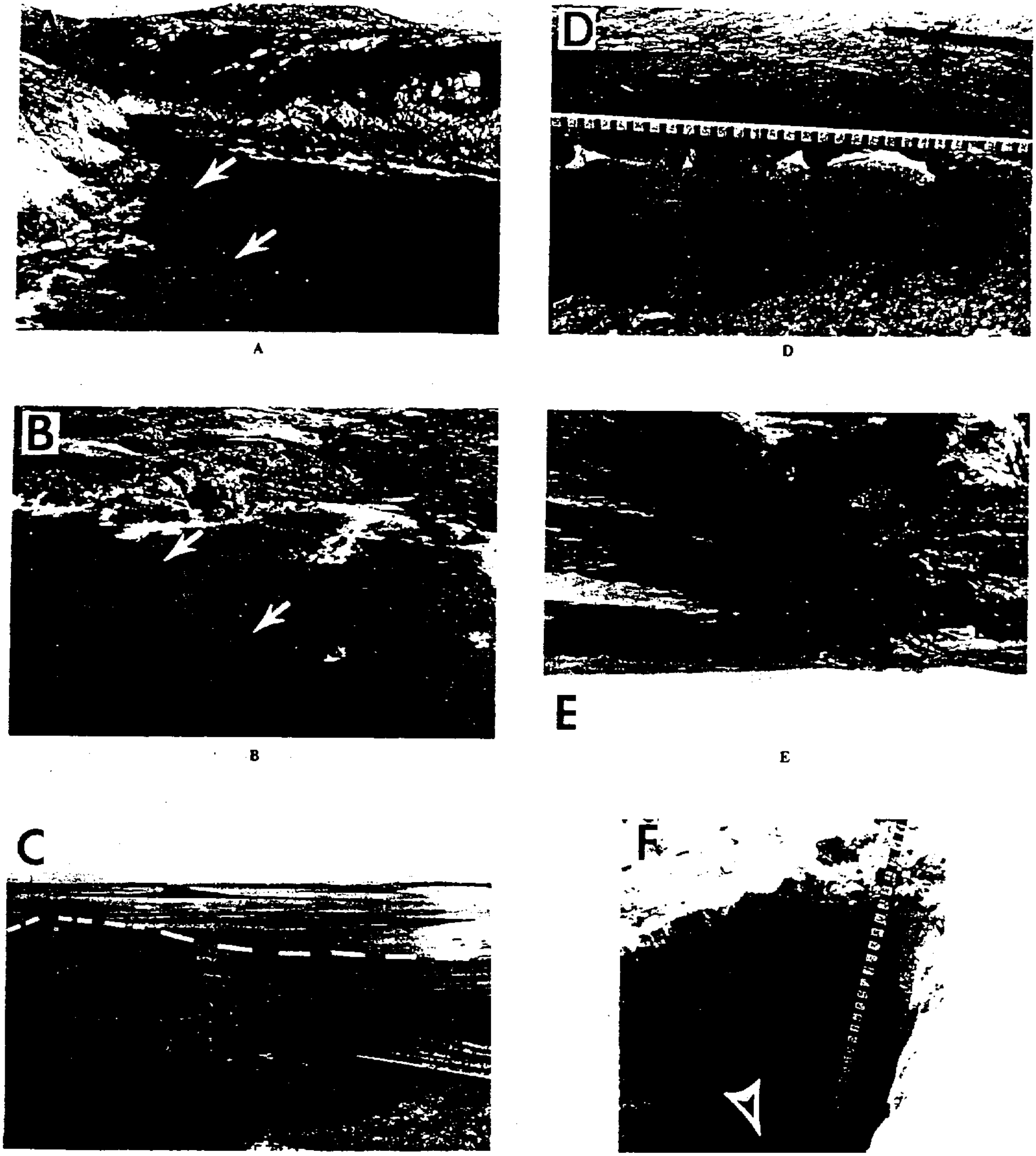

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Figure 4. A. Aerial view of oil (arrows) being held offshore of steeply dipping, rocky shoreline (ESI = 1) at *Urquiola* spill site in Spain. B. Occurrence of the same phenomenon south of *Amoco Cadiz* wreck site. C. Cleanup of heavily-oiled, fine-grained sand beach (ESI = 3) near wreck site; white dashes denote oiled area. D. Oil incorporation into beach illustrated in 4C. Oil was buried less than 30 cm; penetration was limited to 3 cm. Staff across top of trench = 1.1 m. E. View of heavily oiled, coarse-grained sand beach near Portsall. F. Trench showing almost 1 m oil burial (arrow) 2 years after the spill.

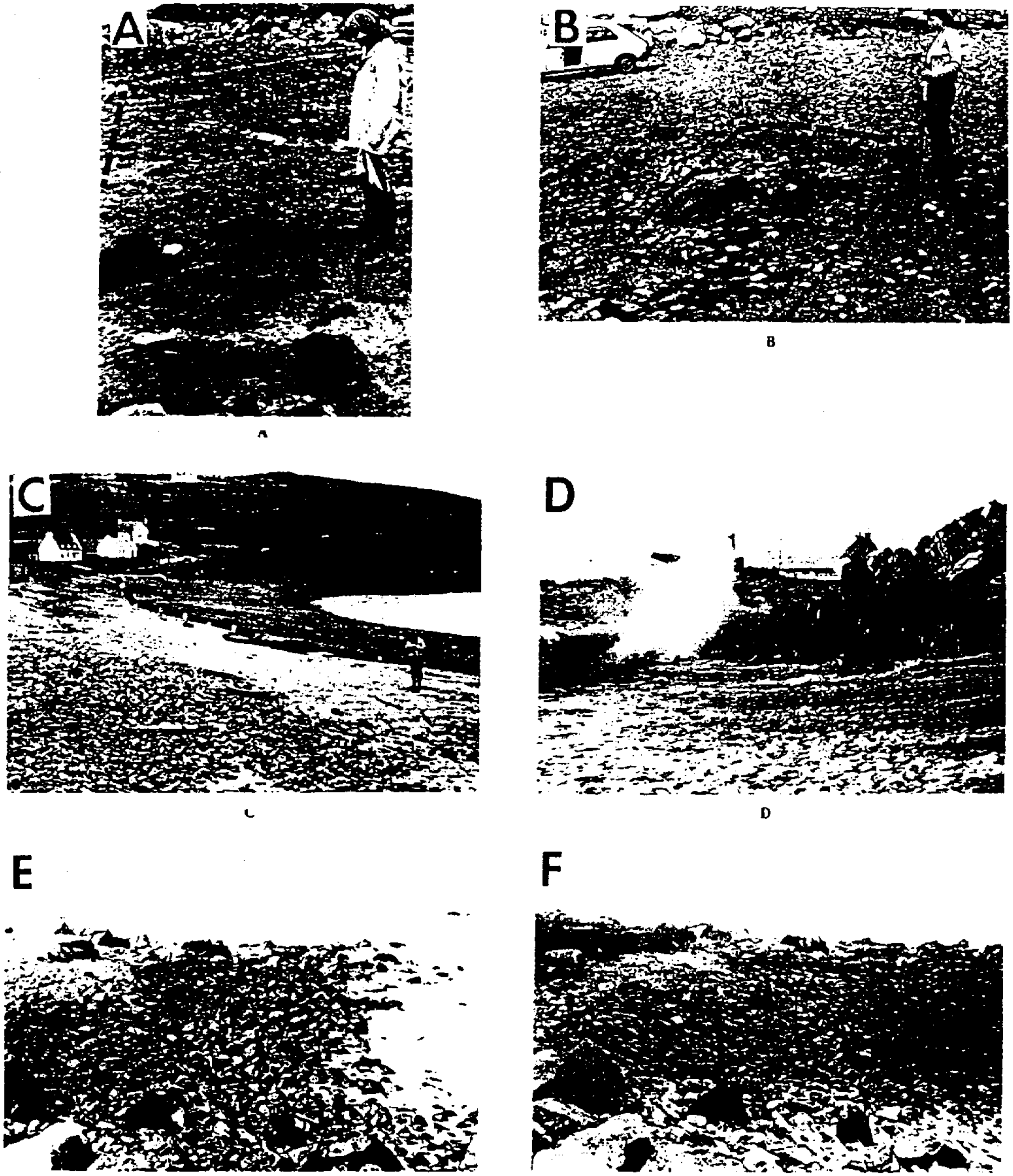

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Figure 5. A. View of asphalted oil (dashed line) on sheltered, mixed sand and gravel beach (ESI = 5) on July 19, 1978. B. Same area on May 14, 1980; the extent of aspohalt was reduced. C. South view of heavily-oiled gravel beach (ESI = 6) at AMC-16 during April 1978; dashes denote heavy oiling. D. Same area (looking north) showing impinging wave action during November 1979; no oil remained. E. Heavily oiled boulder beach (ESI = 5) during initial *Amoco Cadiz* impact. F. Same area on November 7, 1978. Most spilled oil was removed rapidly by wave activity; dashes indicate remaining oil.

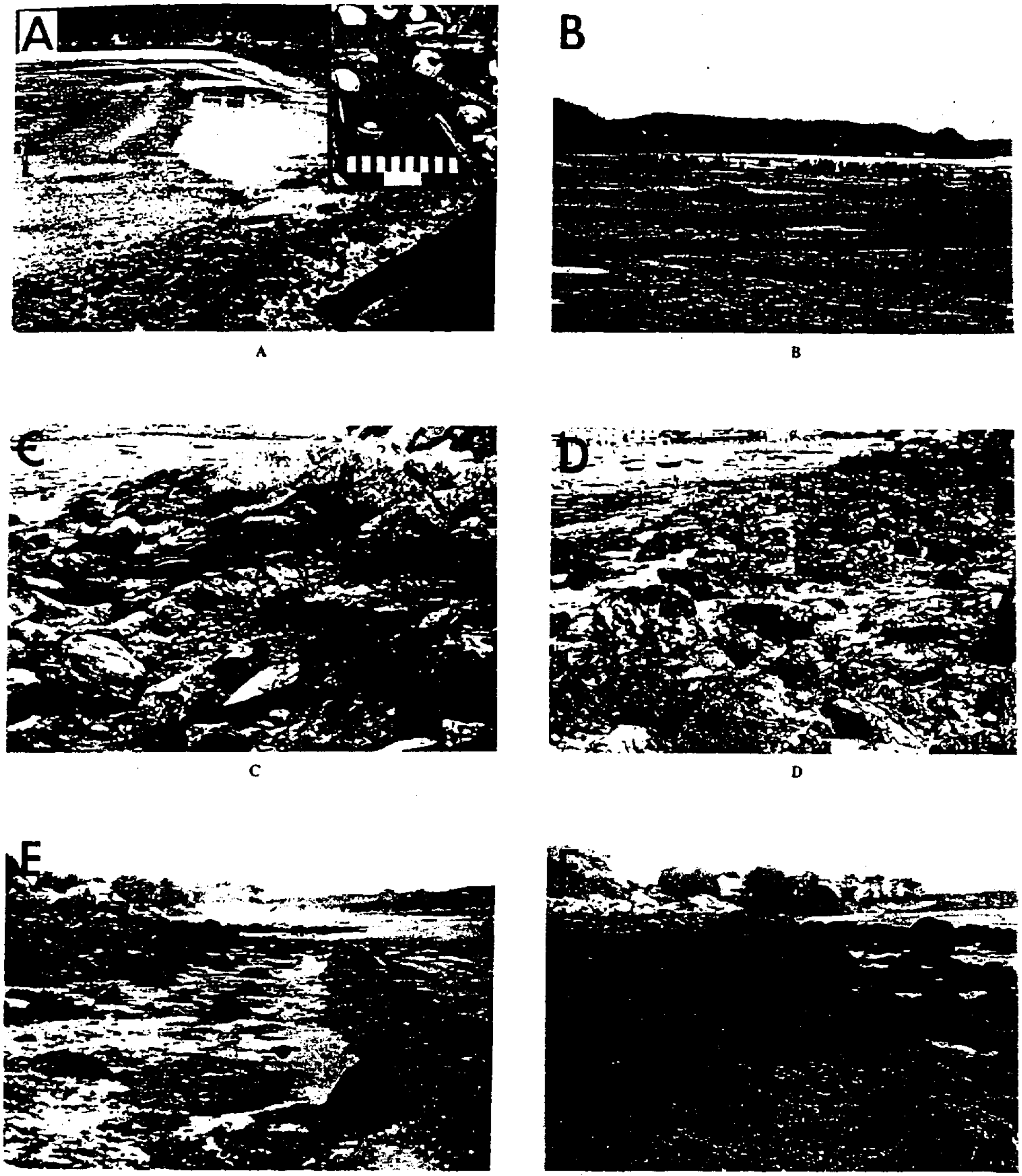

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Figure 6.A. Overview and closeup of recently killed mollusks at exposed sand flat (ESI = 7) at St. Michel-en-Gréve. B. Cleanup operations of St. Michel-en Gréve. Use of oil collection pits may have increased the persistence of oil in the flat's interstitial waters. C and D. Views of sheltered rocky shore (ESI = 8) at Portsall on November 7, 1978 and June 1978 and 1980. After oiling and cleanup, much of the algae was no longer present. By June 1980, many sites still showed incomplete recolonization where *Ascophyllum*, without *Fucus*, was present. E. and F. View of north at the sheltered rocky shore at Portsall in July 1978 and November 1979 showing substantial regrowth of algae (primarily *Fucus*) during intervening year.

Table 2. Descriptions of Oil Persistence After *Amoco Cadiz* Oil Spill[*]

Sensitivity index value and shoreline type	Comments (Duration of pollution)	Observed cleanup
1. Exposed rocky headlands	Composed of bedrock with high impinging wave activity; wave reflection kept most of the oil offshore; no cleanup was needed (days or weeks)	Difficult access; natural processes sufficient.
2. Eroding wave-cut platforms	No good example of oil interaction.	Usually difficult access.
3. Fine-grained sand beaches	Exposed to moderate-to-high wave energy; little penetration into the beach because of compact sand; thin buried layers commonly persisted in depositional areas (months to 1 year)	Easy access; can be cleaned mechanically; buried layers difficult to remove.
4. Coarse-grained sand beaches	Common in semisheltered area in Brittany; greater penetration of oil due to coarser substrate; buried oil common (1 to 2 years)	Easy access; sand removal may cause beach erosion; difficult to use mechanical means.
5. Mixed sand and gravel beaches	Found within some sheltered areas of Brittany; an asphalt pavement formed in some low energy areas of oil deposition. (1 to 2 years; more in sheltered areas)	Easy access; generally hard surface permitted some cleanup of surface oil; high-pressure hosing without sediment removal recommended.
6. Gravel beaches	Showed rapid and deep penetration of oil (1 to 2 years)	Generally easy access; removal of sediment not recommended; high-pressure spraying with mechanical re-working of sediment into surf zone proved most effective.
7. Exposed, compacted tidal flats (moderate to high biomass)	Oil moved rapidly over the flat surface and was deposited along the swashline; varied biological impact: in productive areas, impact was severe (months to 1 year, oil as sheen evident after 2 years)	Easy access; compact flats cleaned easily mechanically; trenches as part of cleanup may have caused increased oiling of interstitial water (visible after 2 years).
8. Sheltered rocky shores	Oil sticks to rocky surfaces; pools of oil between the rocks eventually turned to asphalt (up to 5 years, but most obvious oil effects gone after 2 years)	Access varies, but is often difficult: high-pressure spraying removed algae and organisms as well as the oil; low-pressure washing as the oil comes onshore may be less damaging biologically.
9. Sheltered tidal flats	In areas of low wave energy, oil persisted on the surface as mixed oil and sediment patches; contamination of interstitial water persisted even if the surface was cleaned (more than 5 years)	Access difficult on soft flats; cleanup very difficult and not usually effective; heavy machinery mixed oil into the sediment.
10. Marshes	Oil pooled on the surface of the marsh, killing most flora and fauna. Oil was still very obvious 2 years after the spill. (5 to 10 or possibly more years)	Access varies; heavy equipment further destroyed vegetation and natural drainage patterns; manual cleanup not very effective, but necessary in heavily oiled areas.

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[*] Listed in terms of the ESI (Hayes *et al.*, 1980) which ranks shoreline types in terms of increasing oil effects. Correlation between this system of classification and observations at the Brittany spill site is good.

exposed low-tide terraces and rapidly pushed over the compact sand surface. In contrast, when oil impacted the large tidal flat at St. Michel-en-Grève (with its extremely rich, low intertidal to subtidal population of various mollusks), almost the entire infaunal population was killed (Figure 6A, B), due primarily to dispersed oil in the water column. Two years after the spill, no surface oil was visible at St. Michel-en-Grève or the adjacent beach; however, very light oil sheens were visible on the water surface in trenches in upper portions of the tidal flat. As a result of these observations, the original index was modified to "raise" high biomass, exposed tidal flats from a five to a seven to consider potential biological effects.

Sheltered rocky shores. This shoreline type is common in the many embayments of Brittany and hosts an extensive cover of fucoid algae. Portsall (close to the wreck site) provides an example of oil impact. Much of the mid-to upper-tidal fucoid algae was heavily oiled and by late summer 1978 was scraped off or lost as part of cleanup activities (Figure 6C, D). In the same vicinity, Floc'h and Dioris (1980) observed a gradual attrition of attached plants after oiling, especially at low and high tidal levels. By summer 1979, the extent of algal cover had increased substantially (Figure 6E, F); the feared suppression of reproductive viability was not long-lived (Topinka and Tucker, 1980). However the community structure had altered from *Ascophyllum nodosum* to *Fucus* dominance (as similarly observed after *Torrey Canyon* by Southward and Southward, 1978). Recolonization and growth of fucoid were aided by the presence of mature *Fucus* in the immediate vicinity.

Unfortunately, not all areas recolonized. In *Ascophyllum*-dominated sites (without nearby *Fucus*), a substantial portion of rock surface remained denuded (Figure 6E). *Fucus* propagates by releasing eggs in gelatinous masses which tend to adhere to rocks in the immediate vicinity. Without mature plants, *Fucus* colonization is restricted; *Ascophyllum* will eventually cover these bare areas again, but the process is much slower. If rock scraping and plant removal are undertaken as part of cleanup, it is best to leave some mature plants to act as sources for recolonization.

Sheltered tidal flats. Sheltered tidal flats are very common in the spill site area. Many were heavily oiled and consequently subjected to a large cleanup operation, utilizing much manpower and heavy machinery. Generally, the suface of each flat was free of oil within several months after the spill; however, subsurface contamination was a long-term problem. A moderate-to-heavy oil sheen (with oil droplets in some cases) was present on the water surface in trenches dug along upper portions of the tidal flat, usually within 50 to 100 m of the beach face. Samples of tidal flat sediments from station AMC-4 and Aber W'rach (100 m seaward of the high water line), taken from April 1978 to July 1979, had oil concentrations of 56 to 630 micrograms per gram dry weight (Atlas et al., 1980). Although the polychaete *Arenicola* was very common throughout the area after oil impacts, the continued elevation of petroleum hydrocarbon values undoubtedly affects the infaunal community.

Marshes. In contrast to the large estuarine marsh systems of the East Coast of the United States, Brittany has only small, isolated pockets of marsh grass. Two examples are as follows: (1) a heavily oiled large marsh/tidal flat complex located at Ile Grande, which was subjected to extensive cleanup activities; and (2) a much smaller, heavily oiled marsh fringe located at Station F-137, which was not cleaned. The dominant plants at Ile Grande were *Juncus maritimus*, *Puccinellia maritima*, *Triglochin maritima*, *Halimione portucoides*, and *Limonium*. During the spill, about 7,000 tons of oil were in the area, 3 to 5 cm thick on the marsh surface, and up to 15 cm deep in small pools (Figur 7A, B). A large cleanup operation of both men and machinery began soon after oiling. Surface and pooled oil were drained collected, and pumped up. Both high- and low-pressure spraying of marsh grasses were used also. By July 1978, lower marsh grasses were dead; upper marsh plants survived in some areas (Figure 7C). The removal of soil-binding vegetation caused channel walls to slump into the channel (Figure 7D). The uppe grasses were improving by November, although the lowe grasses as yet showed no comeback. By May 1980, there was slow regrowth of the upper marsh and, finally, some appearance of new growth of the lower marsh grasses (Figure 7C). The area in general, obviously remained oiled. Light oil patches were on the marsh surface; channel sediments were highly contaminated and asphalt pavement was evident along the adjacent rocky shore.

The marsh at station F-137 is also dominated by marsh grasses. Oil impact was limited to a 50 × 150 m section, being heaviest (mostly 1 cm deep, with a few pools 5 to 10 cm deep) within a 10 × 50 m section. As indicated in photographs taken from April 1978 to May 1980 (Figure 7E, F), there is no evidence of recovery in areas where oil was heaviest. As at the *Metula* site, no recovery of the heavily-oiled marsh was evident 2 years after oiling. Thus, there is evidence that cleanup of very heavily oiled marshes is warranted, but it is also obvious that cleanup should be well-controlled and carefully restricted; heavy machinery and human access on the marsh surface should be limited.

Shoreline impact of *Tanio*. The tanker *Tanio* broke up on March 7, 1980, some 60 km off the Brittany coast, while carrying 26,000 tons of fuel from Germany to Italy (OSIR, 1980). The foresection sank with about 11,500 tons, while the aft section was salvage with 7,500 tons. The rest was spilled into the English Channel. Most of the oil drifted onto the Brittany shoreline from March 9 to March 21, 1980, resulting in a 45 percent overlap of areas previously oiled by the *Amoco Cadiz* (Figure 3). In total, oil impacted 197 km of shoreline; 45 km were heavily oiled. In contrast to the case of the *Ammoco Cadiz* where only one-quarter of the total lost impacted the shoreline, most of the spilled *Tanio* oil came onshore. Offshore surveys by Centre pour l'Exploitation des Oceans (CNEXO) and Station Biologique de Roscoff found only trace quantities of oil in the water column or on the bottom (Bemé, 1980). The amount of oil deposited onshore by *Tanio* was roughly one-tenth that of the *Amoco Cadiz* (6,000 versus 62,000 tons).

Cleanup of *Tanio* oil began shortly after impact. Even more so than with *Amoco Cadiz*, *Tanio* oil impacted the "rose coast" tourist area of Brittany. Two months after initial impact, the spill site still showed light-to-moderate oiling, particularly of rocky areas. Emphasis of cleanup activities had switched from removal of major oil concentrations by skimmers and pumps to high-pressure hosing of oil-stained, rocky areas. Cleanup was not restricted to high tourism areas, but included sites well-removed from tourist traffic. Nor was it restricted to sheltered areas where cleanup by natural processes would be expected to take several years. In fact, many areas being cleaned in May were located along the exposed rocky coast where natural cleanup would be expected within 1 year. Clearly, as a cleanup policy that may (or may not) have applicability to the United States, the French system deserves more study from the technical and economic side.

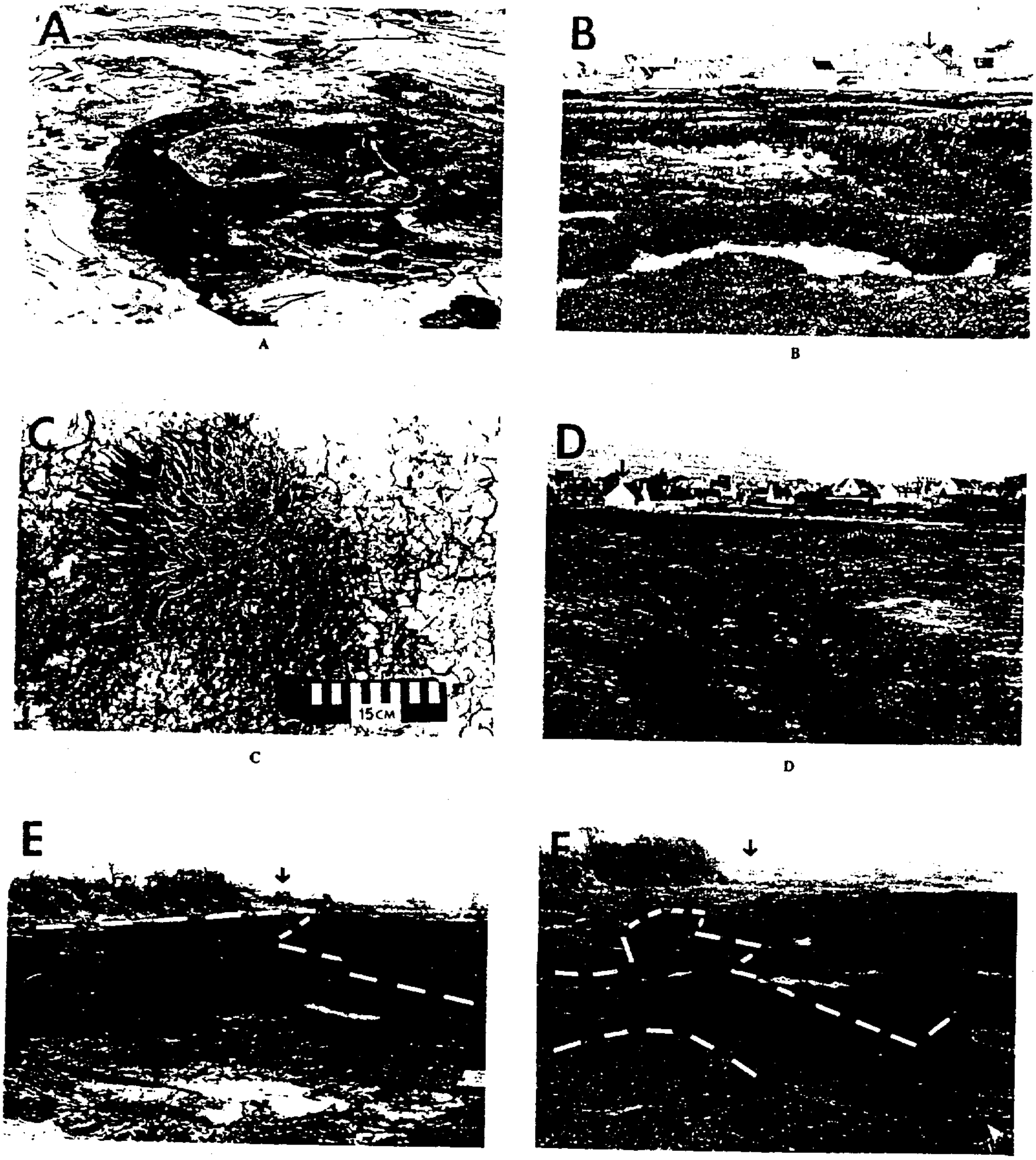

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Figure 7. A. Aerial view of oiled marsh at Ile Grande during initial impact. B. Ground view of heavy oiling at Ile Grande during initial impact; pool in foreground of photo is composed entirely of oil. C. Surviving, lower marsh plants at Ile Grande, May 15, 1980. D. View of same areas as 7B on May 15, 1980; better recovery of upper marsh grass (*Juncus maritimus*) than of lower marsh plants was observed. E and F. Comparison of station F-137 on April 25, 1978 and May 14, 1980; white dashes indicate oiled areas; most heavily oiled areas have not recovered.

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The Fate of *Amoco Cadiz* Oil

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Summary. The *Amoco Cadiz* oil spill (223,000 metric tons) of March 1978 is the largest and best studied tanker spill in history. Of the total oil lost, 30,000 tons (13.5 percent) rapidly became incorporated into the water column, 18,000 tons (8 percent) were deposited in subtidal sediments, 62,000 tons (28 percent) washed into the intertidal zone, and 67,000 tons (30 percent) evaporated. While still at sea, approximately 10,000 tons of oil were degraded microbiologically. After 3 years, the most obvious effects of the spill have passed, although hydrocarbon concentrations remain elevated in those estuaries and marshes that were initially most heavily oiled.

On the evening of 16 March 1978, after losing steerage in the western English Channel, the supertanker *Amoco Cadiz* firmly grounded on rocks a few kilometers offshore of the small fishing village of Portsall, Brittany, France (Fig. 1). Over the next 2 weeks, the entire cargo (223,000 metric tons) of light Arabian and Iranian crude oils and a small amount of bunker fuel C was lost to channel waters during extremely stormy weather and rough seas (*1*). In this manner, the *Amoco Cadiz* entered history as the largest tanker spill as yet to have occurred, being nearly twice the size of the *Torrey Canyon* spill, until then the largest. Because of the enormous size of the spill and the close proximity of several renowned marine laboratories, the spill attracted great scientific attention from investigators in France, the United States, Canada, the United Kingdom, and several other countries. Key summary volumes are included in the references (*2*–*7*). In this article, we attempt to synthesize the extensive data on the physical-chemical fate of the spilled oil during the next 3 years. This article is based primarily on data and discussions from a workshop held in South Carolina in September 1981 (*6*). To guide access to the abundant international literature on the biological impacts of the spill, we also provide a brief overview of these effects, particularly as presented at the November 1979 (*5*) and October 1981 (*7*) symposia held in Brest, France.

One of the more scientifically interesting questions to be answered about a well-studied oil spill is, Where did the oil go? As described in several models (*8*), spilled oil can be degraded or dispersed by several processes, including dissolution, biodegradation, emulsification, evaporation, photochemical oxidation, agglomeration and settling to the bottom, and shoreline stranding. The wide variety of data collected at the *Amoco Cadiz* spill site provides the most complete field evidence to date that would allow one to determine the relative importance of major mass-balance pathways.

The climate of Brittany is temperate, moderated by the strong influence of its maritime setting. Low-pressure areas formed in the North Atlantic are responsible for generating strong westerly winds and high seas. The shoreline is characterized as a low-lying, bedrock-dominated coast with large protruding headlands, large embayments associated with each headland, and smaller, less common, fine-grained estuaries (abers). Offshore sediments are dominated by coarse-grained calcareous sands and gravels, whereas nearshore bays generally have finer grained sands and silts. Tides, strongly prograding from west to east, have a range of 6 to 9 m, which exposed a very large intertidal area to incoming oil. The flora and fauna of the subtidal and intertidal zones of the Brittany coast are very rich and diverse, and support very productive commercial fisheries. In 1976, this region produced about 40 percent of the total fishery products in France (*9*). Principal products, in order of value, are finfish, crustaceans, cultured oysters, other mollusks, and marine algae.

As oil left the breached ship, high waves quickly formed a stable water-in-oil emulsion ("mousse") containing 50 to 70 percent water (*10*). The high wave activity also rapidly distributed oil throughout the nearshore water column. Oil on the surface initially spread eastward as a result of storm winds and tidal currents until a wind shift 2 weeks after the wreck caused a strong oil movement to the southwest. Approximately 15,000 km^2 of offshore waters showed some surface oiling during this period (Fig. 1) (*11*).

Although the *Amoco Cadiz* cargo consisted of two different crude oils in addition to its bunker fuel, authentic cargo samples could not be obtained from the ship prior to breakup because of rough seas. Analyses of surrogate Arabian and Iranian crudes indicated that the oils contained 45 to 62 percent saturated hydrocarbons, 23 to 28 percent aromatic hydrocarbons, and 4 to 5 percent residual (*10*, *12*). Analysis of an authentic "reference mousse" taken by helicopter adjacent to the ship revealed a composition more similar to that of the Arabian crude (39 percent saturates, 34 percent aromatics, 24 percent polar components, and 3 percent residual) (*13*). The gas chromatographic (GC) profiles of the surrogate Arabian and Iranian crudes and cargo oils were similar for saturated hydrocarbons. Only the relative percentages of the saturates and aromatics appear to differ, with the Iranian crude being richer in saturates. Additional chemical characteristics of the oil are presented by Ducreux (*10*) and Calder *et al.* (*12*).

While oil was being transported in or on the surface of the water column, its chemical composition was significantly altered. Evaporative losses caused a loss of lower molecular weight aromatic and saturated compounds, while concurrent microbial degradation caused a depletion of normal alkanes (*n*-alkanes) relative to branched alkanes and an increase in the polar content of the oil even before shoreline impact occurred. The generalized sequence of compositional changes

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taking place in the surface slick and in oiled sediments and tissues is presented in Figs. 2 and 3. The rates of change at any specific site depended on a variety of factors including the extent of original oiling, the mixing energy, and, in sediments, the oxidation state.

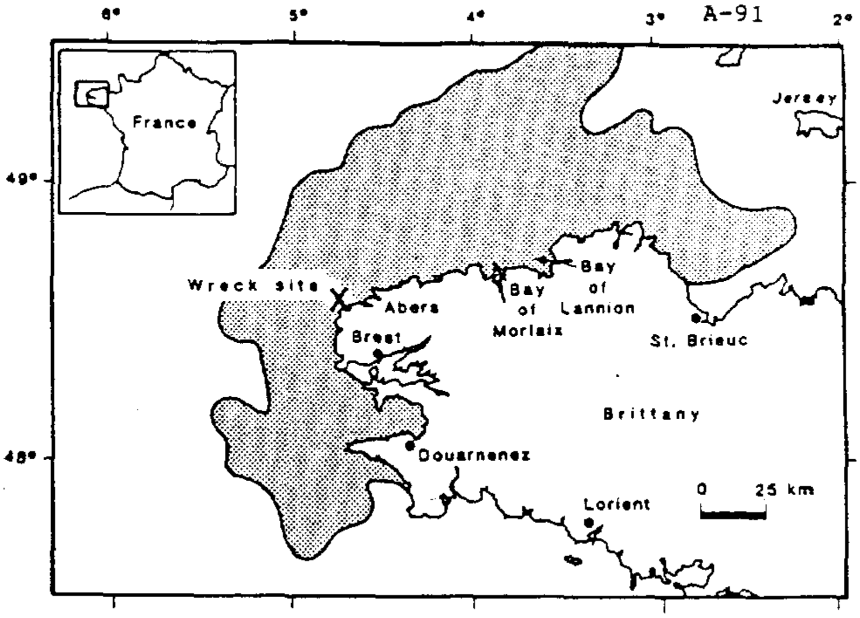

Fig. 1. Maximum distribution of surface slicks between 17 March and 26 April 1978 (*11*). See Fig. 6 for more detail of the spill-affected shoreline.

The saturated fraction of the original oil had an *n*-alkane boiling range from *n*-C_{10} to *n*-C_{40} (Fig. 2A). *n*-Alkanes dominate the GC trace, with branched alkanes appearing as significant secondary features between the *n*-alkane peaks. The aromatic fraction is dominated by two-ringed aromatics (naphthalenes) and, to a lesser extent, by the three-ringed phenanthrene and dibenzothiophene (sulfur-containing aromatic) series. Alkylated aromatics (that is, benzenes, naphthalenes, fluorenes, phenanthrenes, and dibenzothiophenes) dominate over unsubstituted compounds, as is the case for all crude oils. Since alkylated phenanthrenes and dibenzothiophenes are more resistant to degradative processes, they serve as a long-term chemical marker of the oil.

The first stages of the weathering process involved the rapid depletion of lower molecular weight alkanes and single-ringed aromatics (benzenes) through evaporation and a general depletion of *n*-alkanes relative to branched alkanes (for example, isoprenoids) through microbial degradation of unbranched alkanes. The ratio of *n*-alkanes in the *n*-C_{14} to *n*-C_{18} region to five selected isoprenoids in the same region of the GC trace indicates the microbial degradation process (*14*). *n*-Alkanes are more readily degraded than the isoprenoids. This ratio was 4.0 in the original oil but decreased to less than 0.5 as weathering proceeded. The resultant GC traces (Fig. 2, B–D) illustrate these changes which began in the water column and continued to occur (days to weeks) after oil deposition in all sediments. In fact, initial changes in the relative concentrations of hydrocarbons indicate that biodegradation was occurring as rapidly as evaporation in the high molecular weight carbon range (*15*). To our knowledge, this represents the first documentation of a case where biodegradation contributed significantly to the early removal of hydrocarbons from the environment.

After the early changes in the relative proportions of hydrocarbons, the isoprenoid hydrocarbons became more prominent, although they too decreased in absolute concentration. An unresolved complex mixture (UCM) increased in prominence. Naphthenic and naphtheno-aromatic compounds in the UCM were resistant to degradation, whereas components below *n*-C_{14} were no longer present (Fig. 2, C and D).

As weathering proceeded in sediments, the pentacyclic triterpanes (C_{27} to C_{33} cyclic alkanes = naphthenes), which are of very minor importance during early weathering stages, increased in relative prominence because of their refractory nature (Fig. 2, D and E) and became major molecular markers of *Amoco Cadiz* oil (*10, 15, 16*). As the triterpanes and steranes increased in relative abundance, the isoprenoids were degraded and a secondary UCM (C_{25} to C_{31}) emerged. This UCM is presumably formed through microbial or chemical processes taking place mainly in the sediments. Figure 2E illustrates the saturated hydrocarbon assemblage at the end of 2 years' weathering. Beyond 1 year, the isoprenoids were degraded while the triterpanes and the bimodal UCM persisted as recognizable features through June 1981.

The general weathering process of the aromatic hydrocarbons from *Amoco Cadiz* can be separated into three stages. The first step (already described) involved the loss of volatile and soluble compounds (Fig. 3, A and B). Next, the two-ringed aromatics were removed through physical and oxidative processes. The alkylated dibenzothiophene and phenanthrene compounds persisted through June 1981 as the major aromatic molecular markers, and the UCM was the most quantitatively important aspect of the chromatogram.

For comparison, background hydrocarbon assemblages from sediments of this region are shown in Fig. 4, A and B. In general, background or nonspill hydrocarbons are composed of combinations of (i) biologically produced hydrocarbons from marine and terrestrial systems, (ii) compounds produced by the high-temperature incomplete combustion and pyrolysis of fossil fuels, and (iii) other long-term sources of oil contamination (for example, sewage effluents). In the background distributions for this study, the saturated hydrocarbons are largely dominated by higher molecular weight, odd-chain *n*-alkanes of a terrigenous plant source and a UCM of general long-term anthropogenic origin. Aromatics are dominated by three- to five-ringed polynuclear aromatic hydrocarbons of a pyrolytic rather than petroleum origin.

Oil in the Water Column

Several French and British cruises were undertaken between March and September 1978 to characterize the distribution and concentration of *Amoco Cadiz* oil in the water column (*11–13, 17, 18*). Water samples were extracted and analyzed by standard ultraviolet fluorometric methods (*19*). Oil concentrations were found to range from 3 to 20 µg/liter in the offshore zone (49° to 49°30'N), from 2 to 200 µg/liter in the nearshore zone (shoreline to 49°N), and from 30 t 500 µg/liter in Aber Wrac'h and Abe Benoit. These values are comparable t those found at other surface spills [*Ekofisk*, 30 µg/liter (*20*); *Argo Merchant*, 45 parts per billion (ppb) (*21*); *Arrow*, 4 ppb (*22*)] but are much lower than th

7000 ppb observed at the subsurface *Ixtoc I* blowout (*23*). By mid-April 1978, concentrations in the offshore region had decreased to background values (< 2 μg/liter). In nearshore areas elevated values were obtained until mid-May, and until September within the estuaries.

During the first 3 weeks, ~20,000 metric tons of oil were incorporated into the water column; this estimate is based on average concentrations and four complete water changes (Table 1). Indirect evidence (oxygen depletion) indicates that an additional 10,000 tons of oil were degraded by microorganisms (*24*). This would raise the total oil content in the water column to some 30,000 tons or 13.5 percent of the amount spilled.

Oil in Subtidal Sediments

Oil was transported to the subtidal sediments of three regions: (i) offshore areas composed of coarse-grained calcareous sediments and exposed to high current velocities, (ii) the more sheltered Bay of Lannion and Bay of Morlaix composed of finer grained sediments, and (iii) the very sheltered estuaries at Aber Wrach'h and Aber Benoit, which contain mostly silts and clays. An extensive array of sampling techniques and analytical work was carried out on the oiled sediments collected from these areas (*2–6, 25*).

During the first month of the spill, ~18,000 tons of oil were incorporated in subtidal sediments (Table 2). Three months later, hydrocarbon concentrations in these sediments were generally lower than the initial oil concentrations (*17*), although exact station comparisons were difficult. Detailed follow-up surveys (293 stations) in the Bay of Lannion and Bay of Morlaix revealed a decrease in oil content from 7600 to 1800 tons by July-August 1978, and to 800 tons by August 1979 (*25*). By August 1980, most stations had little or no oil [< 15 parts per million (ppm)], although three sites still showed values over 100 ppm as measured by infrared spectroscopy. Cleansing was attributed to storm processes, although microbial activity was not measured.

In contrast to the case for offshore sites that underwent a rapid sediment cleansing, sheltered interior sites with fine-grained sediments showed elevated oil concentrations (600 ppm) through June 1981 (Fig. 5). Oil persistence in subtidal sediments appears related to the physical energy of the particular site and the type of sediment.

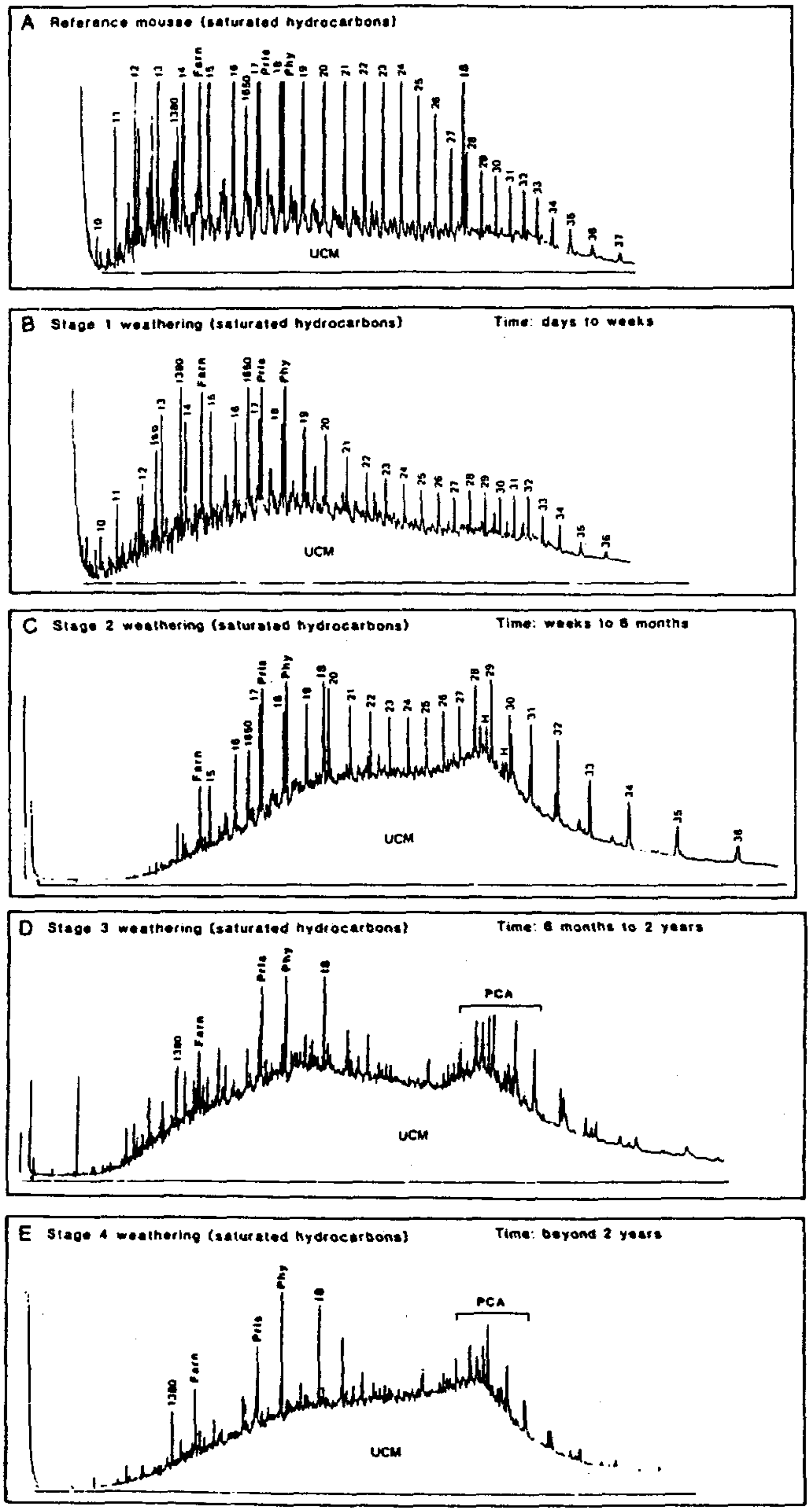

Fig. 2. Capillary gas chromatographic (GC) traces of compositional changes in saturated hydrocarbons of *Amoco Cadiz* oil representative of generalized oil weathering patterns in the oil slick, sediments, and tissues [*10, 11 . . . 37* refer to the number of carbons in *n*-alkanes: *Farn* = farnesane; *Pris* = pristane; *Phy* = phytane; *Iso* = unidentified isoprenoid alkanes; *1380* and *1650* = other isoprenoid hydrocarbons; *H* = hopanes; *PCA* = polycyclic aliphatics; *UCM* = unresolved complex mixtures; *IS* = internal standard = androstane (in C, D, and E) or cholestane (in A); no internal standard in B] (*16*). Indicated times are only approximate.

Oil in the Intertidal Zone

On the basis of detailed measurements of oil quantity at 19 stations and extrapolation over the entire oiled zone derived from additional ground stations and aerial photographs, it was estimated that some 62,000 tons of oil came onshore during the first weeks of the spill (*26*). However, by the end of April 1978, this quantity had decreased to ~ 10,000 tons, although the extent of oiled shoreline increased from an initial 72 km (Fig. 6) to over 320 km as large individual slicks broke up and spread. After this initial increase, the extent of obviously oiled coast declined rapidly at first and then at a much slower rate as a result of the persistence of oil in very sheltered localities (Fig. 7). By November 1979, oil remained along only 50 km of coast. This slowly decreasing trend presumably would have continued had not the tanker *Tanio* spilled some 7000 tons of oil in March 1980 over roughly half the shoreline previously impacted by *Amoco Cadiz* oil (*27, 28*).

The most efficient shoreline-cleansing process resulted from wave and tidal action. Cleanup operations, in which thousands of workers participated until September 1978, removed approximately 25,000 tons (*4*). Microbial activity was responsible for the degradation of oil remaining after the cleanup, especially in sheltered areas (*29*).

Several intertidal sites were chemically monitored to determine oil degradation rates and products. Detailed GC analysis of hydrocarbons from fine-grained intertidal sediments (for example, Ile Grande marsh and Aber Wrac'h) confirm the compositional trends noted in Figs. 2 and 3 as well as the overall decrease in concentration with time. By mid-1981, hydrocarbon concentrations in intertidal sediments varied greatly, from near background levels as observed at sites in Aber Wrac'h to over 11,000 ppm of highly weathered oil (beyond chemical recognition) at Ile Grande (*16*). Even the alkylated aromatic markers, evident through June 1980, were largely absent, having been depleted as a result of combined weathering processes.

The behavior of oil in the upper intertidal sediment of Aber Wrac'h contrasted strikingly with that of adjacent lower intertidal-subtidal sediments. Whereas the upper intertidal sites were virtually clean by June 1981 (Fig. 5, stations 51 and 61), high oil concentrations still remained in the deeper areas, probably due to the greater extent of oiling and the anoxic conditions of the lower intertidal and subtidal regions.

Table 1. Calculation of the total hydrocarbons incorporated into the water column during th first 3 weeks of the *Amoco Cadiz* spill.

Zone	Depth of mixing (cm)	Area (km^2)	Average concentration above background* (μg/liter)	Standing crop of oil† (tons)	Total (tons
Offshore (49° to 49°30'N)	30	150 by 30	10	2,250	9,00
Nearshore (shore to 49°N)	30	150 by 30	20	2,700	10,80
Estuaries (Benoit and Wrac'h)	30	12 by 0.3	120	120	1
Total (3 weeks)					19,81

*See (*11, 12, 17, 18*). †Amount of oil at one given time. ‡Based on four complete water changes.

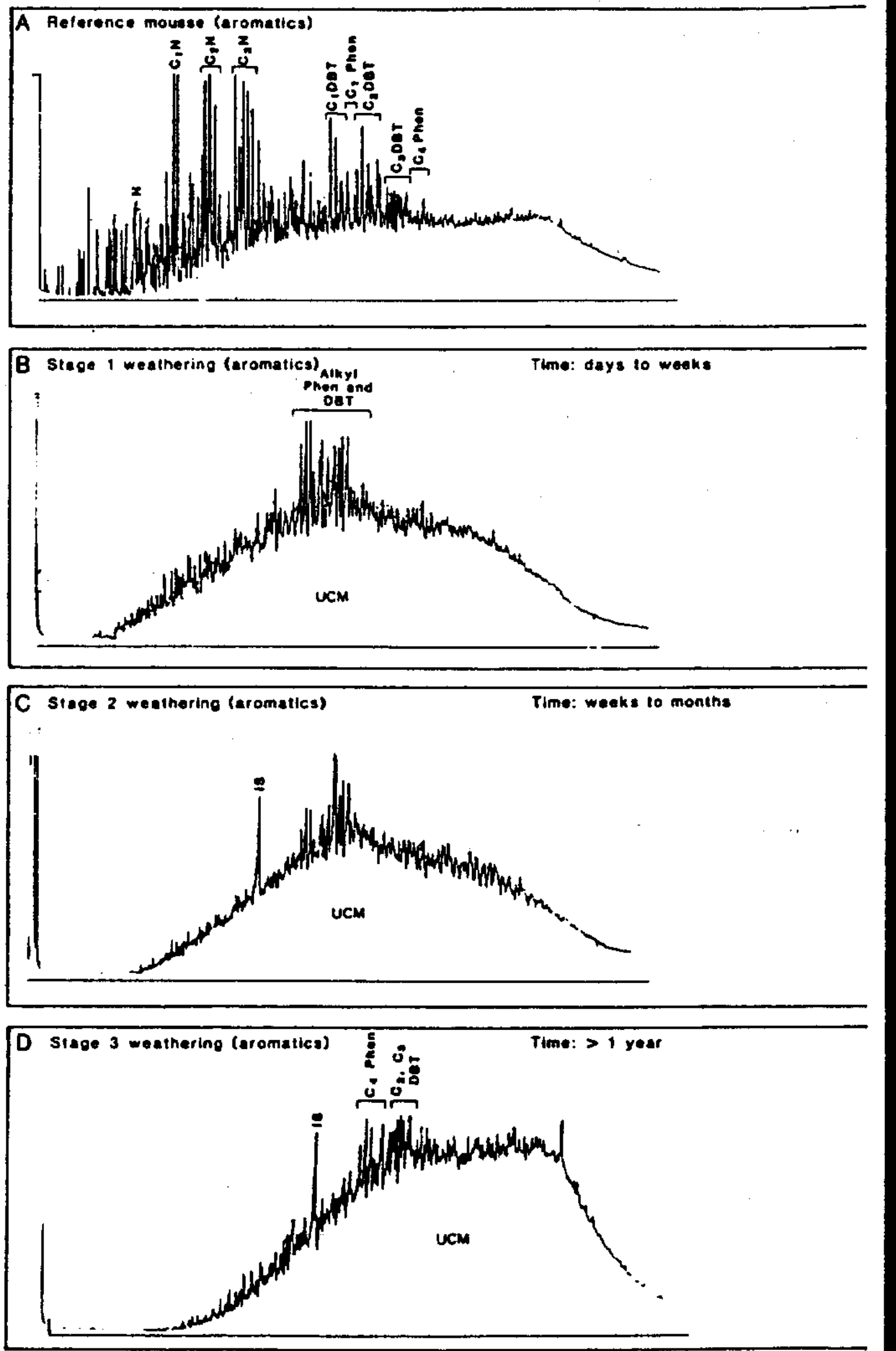

Fig. 3. Capillary GC traces of compositional changes in aromatic hydrocarbons of *Amoco Cadi* oil representative of generalized oil weathering patterns in the oil slick, sediments, and tissue (*N* = naphthalene; *DBT* = dibenzothiophene; *Phen* = phenanthrene; C_1, C_2, C_3, C_4 indicat the number of alkyl substitutions on aromatic molecules; *UCM* = unresolved complex mixture *IS* = internal standard = deuterated anthracene) (*16*). Indicated times are only approximate.

In intertidal areas, concentrations decreased with depth to roughly 20 cm, although fine-sectioning of the core indicated some variability in this trend, especially among individual hydrocarbon components (Fig. 8). The physical movement of sand as part of the natural erosional-depositional beach cycle (*26*), and possibly the downward migration of oil influenced by tidal action (*30*), caused a much deeper burial of oil (up to 1 m). In addition to variability with depth, the severe patchiness of the distributed oil, as well as the secondary input of *Amoco Cadiz* or *Tanio* oil, or both, at several stations (*16*), severely complicates the short-term interpretation of chemical concentration data.

Although physical processes were the major cleansing mechanism at moderate- to high-energy beaches and cleanup was responsible for the superficial removal of oil at nearly all heavily oiled locations, microbial activity played a principal role in degrading oil remaining in sheltered environments. On the basis of oil degradation rates measured with the use of radiolabeled tracer hydrocarbons, it is estimated that microorganisms would be capable of degrading some 0.5 μg of oil per day per gram of sediment (29). Superimposing this rate over a 100-m average intertidal zone for the 320 km of shoreline that was oiled, we estimate that some 880 tons of oil could have been degraded by March 1980, the time of additional oil inputs from the *Tanio* spill.

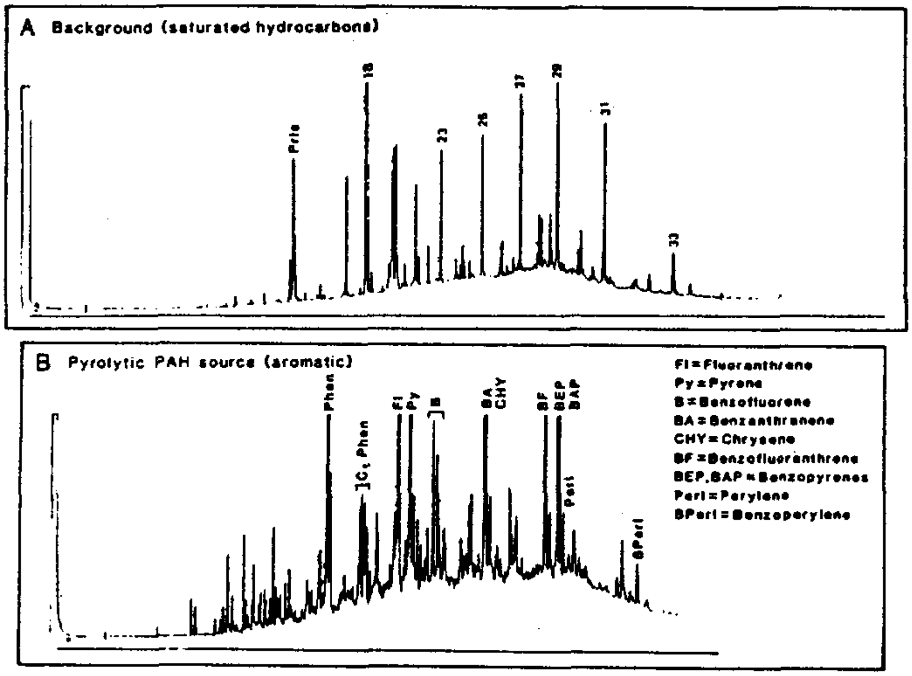

Fig. 4. Capillary GC traces of the typical background hydrocarbon distribution not influenced by *Amoco Cadiz* oil: (A) saturated hydrocarbons (the abbreviations not listed are the same as in Figs. 2 and 3); *IS* = internal standard = androstane; (B) aromatic hydrocarbons (*16*); *PAH* = polynuclear aromatic hydrocarbons.

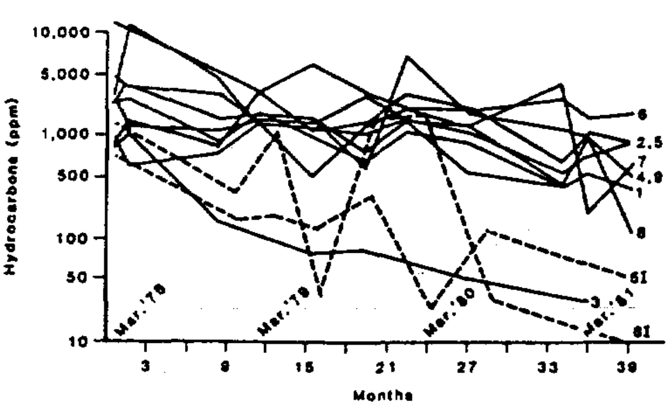

Fig. 5. Hydrocarbon concentrations in Aber Wrac'h sediments from March 1978 through June 1981. Samples at stations 1 through 9 were analyzed by infrared spectroscopy (*48*); samples at stations 51 and 61 [intertidal (*16*)] were analyzed by GC.

Oil residing in subsurface sediments was more persistent. For example, changes in aromatic hydrocarbons, which dominated the hydrocarbon assemblage in sediments, occurred more slowly in deep muddy sediments than in surface sandy sediments where mixing energy is greater (*31*). Microbial hydrocarbon biodegradation is often considered an oxygen-dependent process so that limited oxygenation might explain slower biodegradation. However, even under carefully controlled anaerobic laboratory conditions with the use of muddy sediments, radiolabeled hydrocarbons were still slowly oxidized (*31*). Although there exists the potential for anaerobic biodegradation in these sediments, the rates are probably 40 to 300 times slowe than under aerobic conditions.

Biological Effects

The biological and ecological effects o the *Amoco Cadiz* spill have been studied extensively by researchers from France Canada, the United Kingdom, and the United States (*2–7*). Selected observations are briefly reviewed here to direc readers to the appropriate literature, especially where more recent updates are available (*6, 7*).

Three principal classes of biologically associated values are subject to impac from oil spills: (i) the commercial marke values of fisheries products may drop because of contamination or tainting; (ii the productivity of fisheries species may be altered directly through toxic, pathological, physiological, or reproductive effects, or indirectly through similar effects on other species required as food for the commercial species; and (iii) noncommercial species or communities o aesthetic value (for example, birds) may be impacted through the processes listed in (ii). Effects of the *Amoco Cadiz* spill were manifested through most of the mechanisms listed above.

In the initial few days of the spill mortalities of rocky bottom–dwelling finfish species occurred near the wreck

Table 2. Calculation of *Amoco Cadiz* oil deposited in subtidal sediments based on a specific gravity for oil of 1.0 g/cm^3 and a specific gravity for sediment of 1.5 g/cm^3.

Location	Area (km^2)	Average concentration (ppm)	Depth (cm)	Total (tons)
Nearshore	1806*	35†	10‡	7,111
Bay of Morlaix and Bay of Lannion	322	210§	10‡	7,607
Aber Wrac'h	2.6	1,887–12,000‖	20 (*47*)	1,919
Aber Benoit	2.1	746–28,475¶	20 (*47*)	1,558
Total (1 month)				18,195

*75 percent of the area considered to be nearshore (*11*); 25 percent considered to be nonoiled rocky area based on grab sampling. †70 ppm (nonpurified extract) (*11*) is halved to account for petroleum hydrocarbons (purified extract) only (*48*). ‡Samples taken by several types of grab samplers. §Average of ten sites (*11*). ‖Two zones: 2.5 km^2 × 1,887 ppm, and 0.14 km^2 × 12,000 ppm (*11*). ¶Three zones: 0.9 km^2 × 746 ppm, 1.12 km^2 × 3,021 ppm, and 0.04 km^2 × 28,475 ppm (*11*).

site, but these species are little sought after and the impact was poorly quantified. Experimental trawls conducted during 1978 and 1979 in the Bay of Morlaix and Bay of Lannion suggested a scarcity of several well-known finfish species, but many had returned to normal population densities by the end of 1978. The most important impact on finfish probably was the reduction of flatfish reproduction, especially in the Bay of Lannion where young soles were absent in 1979 (*32*). Flatfish growth in Aber Benoit and Aber Wrac'h was reduced during 1978, coincident with an increase in reproductive pathologies and fin necroses (*33*). Although these disturbances have strong implications for the nearshore fisheries population as a whole, it is unlikely that changes in future catches will be attributable to the *Amoco Cadiz* spill because of the high natural variability of the catch data.

The catch of edible crabs (*Cancer pagurus* and *Lithodes maia*) in 1978 was lower than expected; however, by 1979, the catches of these species as well as lobsters (*Homarus vulgaris*) and rock lobsters (*Palinurus vulgaris*) were normal. The low percentage of egg-carrying female lobsters observed in 1978–1979 could lead to reduced recruitment in 1982–1984 (*32*).

In the intertidal zone, the spill most severely affected the oyster mariculture industry located in Aber Wrac'h and Aber Benoit and the upper Bay of Morlaix. Initial mortalities in the abers were 20 to 50 percent of the total population. Those oysters not directly killed were so heavily contaminated by hydrocarbons that they could not be marketed; this resulted in the intentional destruction of 5000 tons of oysters in 1978. Contaminated oysters transported to clean areas showed some depuration of biologically assimilated residues [consistent with findings from the *Tsesis* spill (*34*) and numerous laboratory studies (*35*)]. New oysters reintroduced into the abers in January 1979 became strongly contaminated (150 to 190 ppm) except in a few areas where the oiled sediment had been removed and replaced (*32*). Effective restocking occurred in 1980, and oyster production in the abers had resumed by 1981 (*36*). The situation was somewhat different in the upper Bay of Morlaix. Few mortalities occurred in the original oyster stock, and by spring 1979 hydrocarbon concentrations in the oysters had decreased to concentrations acceptable for marketing (*32*).

Other mollusks commercially harvested in the impact zone include scallops (*Pecten*), cockles (*Cerastoderma*), mussels (*Mytilus*), and several species of venerid clams. Although the accumulation of hydrocarbons and dibenzothiophenes was documented in several species and histopathological anomalies were detected in some (*33*), no changes in overall productivity could be quantified (9).

No significant effects of the *Amoco Cadiz* spill have been documented for the production of kelp or other algae, which are extensively harvested in Brittany for fertilizer and silage, and for the manufacture of alginates. The growth of kelp (*Laminaria*) appeared impeded in April 1978 but returned to normal for the balance of 1978 and was apparently stimulated in 1979 (*32*). In Portsall Harbor, where algae (primarily *Fucus* and *Ascophyllum*) were physically removed from rocks and breakwaters during cleanup, reestablishment of a superficially abundant community had occurred by 1980, although the community structure had been altered (*28*).

The intertidal marsh area behind Ile Grande was heavily oiled during the spill (see Fig. 6 for location). An extensive manual and mechanical cleanup operation caused additional damage by trampling and soil removal. In areas where surficial oil was mopped off the marsh and picked up without disturbing surface sediments, several marsh plants (mos notably, *Halimione*, *Puccinellia*, and *Juncus*) in places survived the spill. By 1979, limited repopulation had started especially by annual species (for example, *Salicornia*) (*37, 38*). In areas where surface sediments were removed, soi

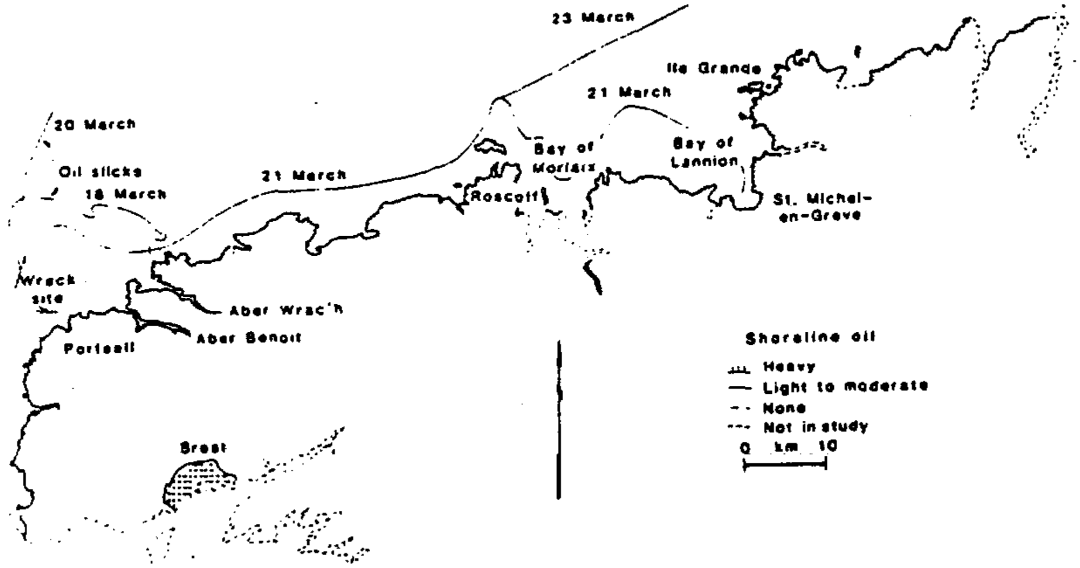

Fig. 6. Initial distribution (March–April 1978) of *Amoco Cadiz* oil along the shoreline (*28*).

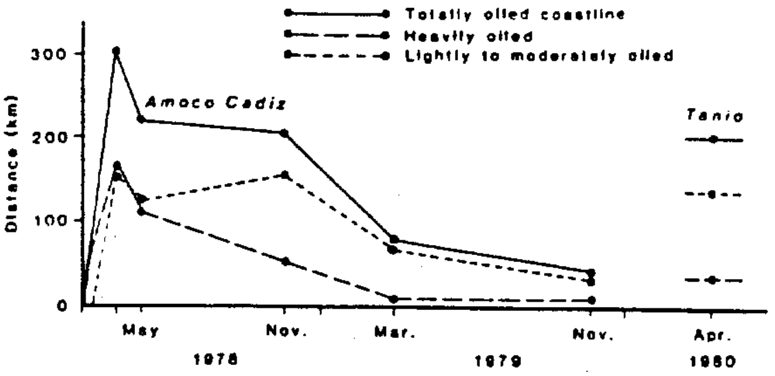

Fig. 7. Extent of shoreline oiling from March 1978 to April 1980 (*26*).

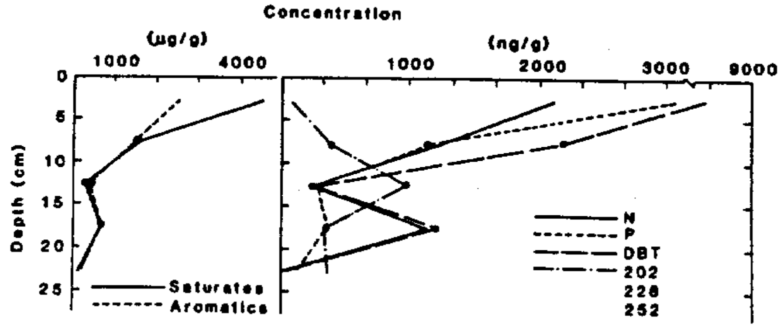

Fig. 8. Depth profiles for hydrocarbon components from a representative core taken at Ile Grande in March 1979 [*N* = total naphthalene; *P* = total phenanthrene; *DBT* = total dibenzothiophene; *202*, *228*, and *252*, indicate summation of polynuclear hydrocarbons (not attributable to *Amoco Cadiz*) of molecular weights 202, 228, and 252] (*16*).

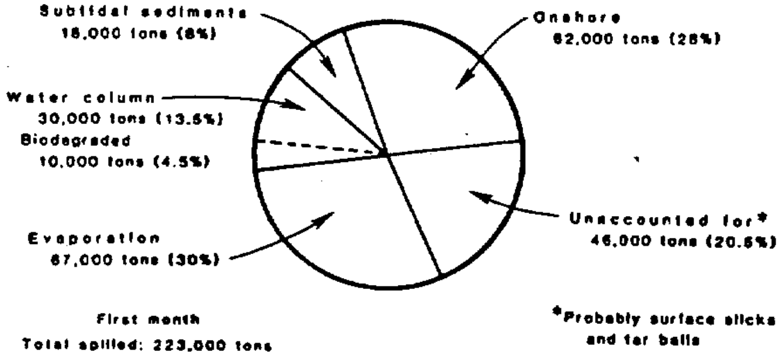

Fig. 9. Quantitative estimate of *Amoco Cadiz* oil dispersal components for the first month of the spill.

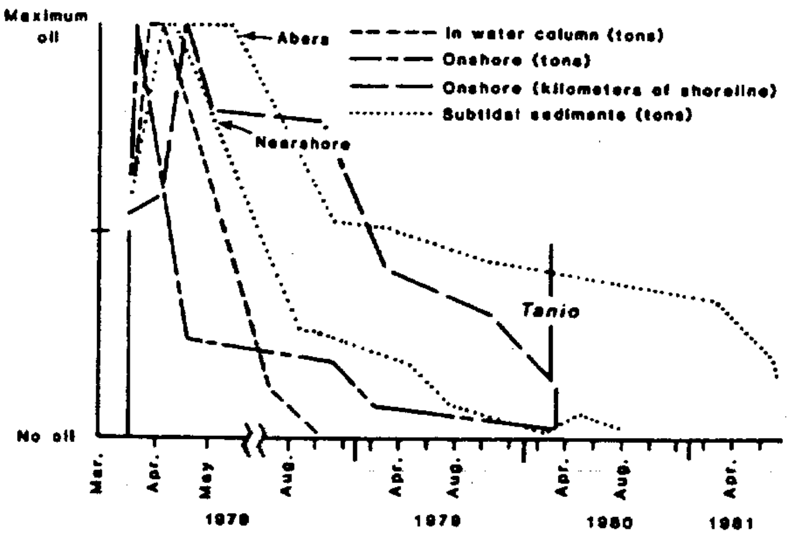

Fig. 10. Synthesis of data indicating the relative persistence of *Amoco Cadiz* oil in various components, March 1978 through June 1981.

nutrients were depleted and little if any natural succession has occurred. However, planting aided by fertilizers has been successful in these areas, especially for *Halimione* and *Puccinellia* (*36*, *38*).

Intertidal and nearshore subtidal invertebrate communities suffered heavy initial mortalities in 1978 with the nearly complete disappearance of some species or groups in certain areas (for example, *Ampeliscus* amphipods in the Bay of Morlaix and Bay of Lannion, and *Tellina fabula* clams in the lower intertidal zone at St. Michel-en-Greve on the south shore of the Bay of Lannion). These initial losses were followed by invasions (or population explosions) of opportunist species such as polychaetes (*Mediomastus* and *Arenicola*) and nematodes, especially in 1979 (*37*, *39*, *40*). Species richness increased slowly after the initial impact. By 1980 or 1981, most species had reappeared and were undergoing typical seasonal fluctuations. The upstream ends of the abers showed the slowest recovery (*40*). Microbial communities involved in anaerobic decomposition within sediments were not significantly affected by *Amoco Cadiz* oil although evidence suggests that norma carbon and electron flow could be inhibited by unweathered oil (*31*).

The chemical program associated with these biological studies centered on determining alteration products and hydrocarbon concentrations within key species. For the most part, analyses of fish tissues revealed only sporadic direct evidence of recent unaltered petroleum residues in spite of detectable histologica changes, thus indicating a probable metabolic transformation of assimilated oil (*15*). However, residues were readily apparent in oysters although the origina *Amoco Cadiz* oil composition was altered through selective uptake and depuration processes. The most persisten chemical feature of oil-contaminated oysters (until June 1980) was the dominance of the alkylated phenanthrene and dibenzothiophene compounds in the tissues (as in Fig. 3B) (*15*, *41*, *42*). The concentrations of these aromatic compound classes were 1 to 20 ppm (compared to a total hydrocarbon concentration of 400 to 1000 ppm). Concentrations generally decreased over the 3 years with slight to moderate indications of significant depuration, depending on sampling location. The transplantation of contaminated oysters to clean sediment accelerated the depuration process but did not result in complete purging of *Amoco Cadiz*–related aromatic hydrocarbons (residual concentrations of 40 to 80 ppm) (*42*).

Conclusions and Discussion

We estimate that during the first month the 223,000 tons of oil spilled by *Amoco Cadiz* were dispersed as shown in Fig. 9. The amount incorporated in the water column is greater than that observed at other spills (*43*), but this excess is probably due to the very high wave energy associated with the *Amoco Cadiz* site, which forced oil into the water column over a large surface area. Evaporation remains a major unmeasured component; however, indirect evidence from compositional changes, as well as several laboratory studies (*44*), indicate a 20 to 40 percent loss through evaporation. We consider an average of 30 percent a reasonable estimate. Photochemical oxidative processes were probably insignificant in the high-energy Brittany environment, in distinct contrast to the case for the *Ixtoc I* spill (calm water and warm climate) where they were important (*45*).

Figure 10 presents a generalized scheme of relative oil degradation within the various spill components. Initially, oil in the water column was replenished rapidly as oil was removed from the shoreline by wave activity. Replacement slowed as oil leached out of the remaining oiled shorelines and bottom sediments. The lighter fractions of incoming oil were probably degraded by microbial activity and evaporation. The high wave energy associated with the Brittany coast appears to be very important in maintaining an adequate supply of nutrients (oxygen, nitrogen, and phosphorus) and in redistributing the oil as a fine emulsion. The high wave energy provided optimal conditions for high rates of biodegradation. Residual, nonbiodegradable components of the oil persisted as small tar balls or particles.

Oil was transported to the bottom while surface slicks were still extensive, but additional inputs occurred as oil was carried seaward off the beaches, particularly 2 to 6 weeks after the ship's breakup (Fig. 10). The cleansing rates of subtidal areas after oiling differed, depending on sediment type and the physical energy of the particular site. Oil deposited in coarser grained localities exposed to swiftly moving currents was cleaned fairly rapidly. However, in sheltered areas having fine-grained sediments, microbiological rather than physical processes dominated so that the rate of degradation was much slower. In fine-grained Aber Wrac'h, the hydrocarbon content of the sediment remained elevated more than 3 years after the spill.

Oil deposited on the shoreline was removed primarily by wave action and cleanup activities on the short term (several months) and by microbial degradation on the long term. However, since rapid biodegradation is restricted to aerobic surface sediments, oil remaining buried in anaerobic layers may persist for several more years. Chemical evidence of the *Amoco Cadiz* oil spill remains at the upper ends of Aber Wrac'h and Aber Benoit and at the intertidal marsh at Ile Grande. Particularly at Ile Grande, patches of asphalt-like material can still be found in upper intertidal rocky areas. Similar long-term oil persistence in low-energy environments has been observed at the West Falmouth, *Arrow*, and *Metula* oil spills (*46*). Petroleum residues and the remnants of certain ecological changes at the *Amoco Cadiz* site are expected to persist for over a decade, particularly where oil is buried in anaerobic zones below the surface.

References and Notes

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Fate and Persistence of Crude Oil Stranded on a Sheltered Beach

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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

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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

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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.

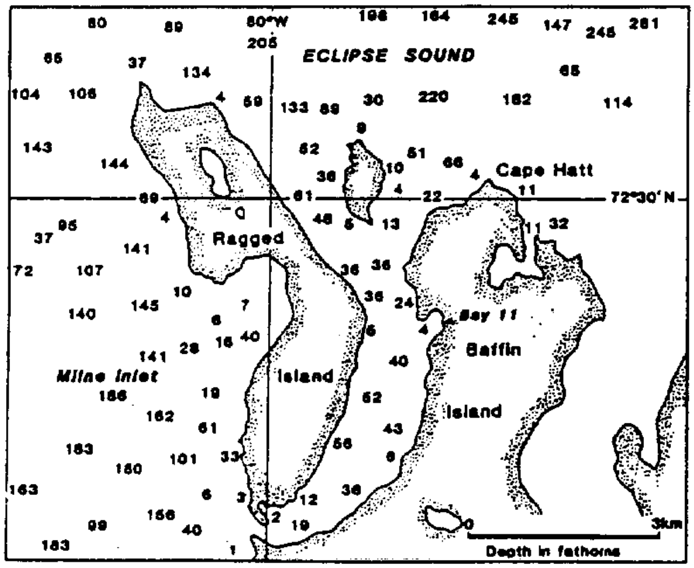

FIG. 1. Location of Bay 11 in Ragged Channel, Baffin Island, N.W.T. (water depths are shown in fathoms).

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.

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)

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

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.

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

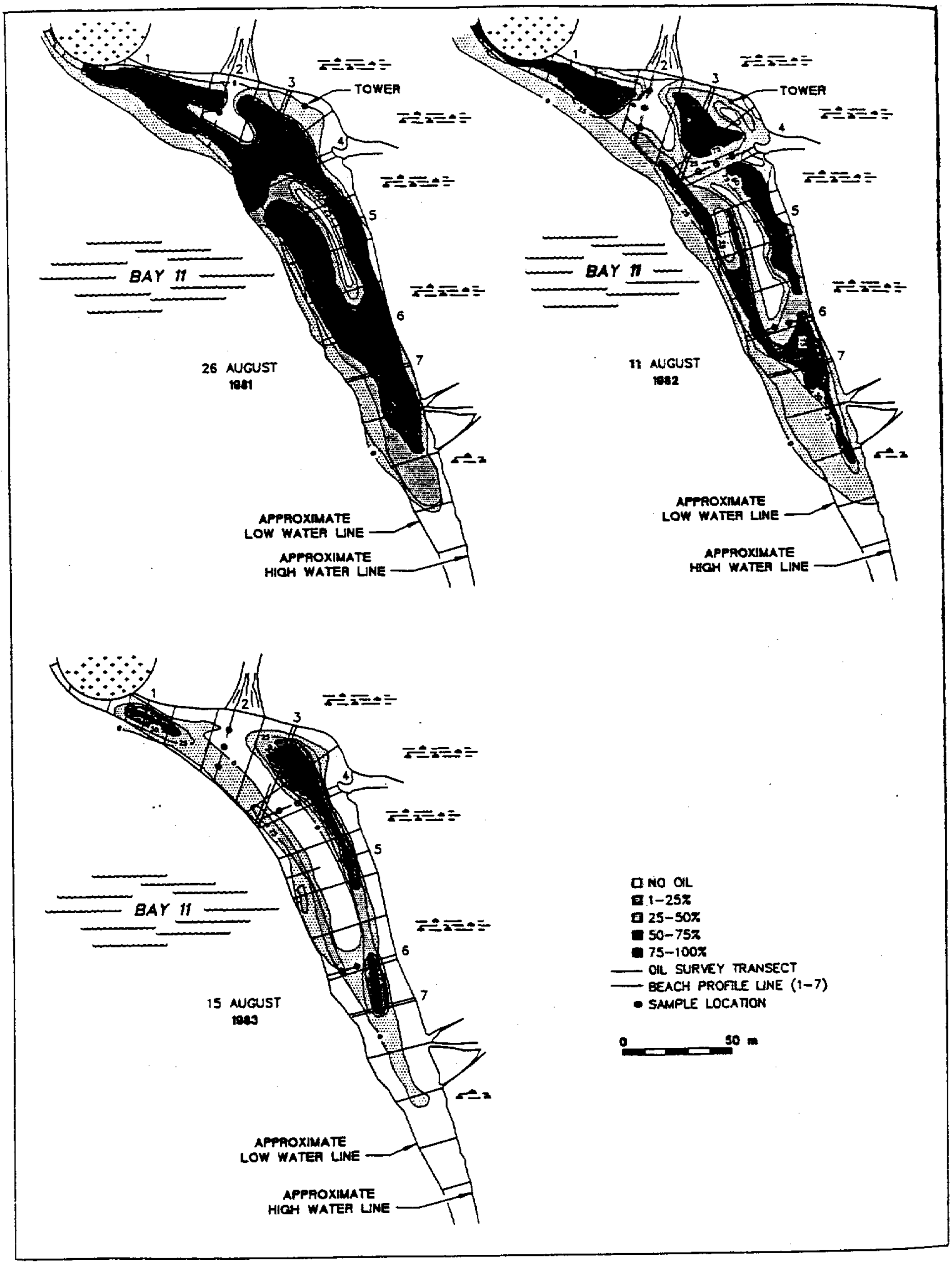

FIG. 2. Mapped surface oil distribution. Observations were made along the cross-beach transects (solid lines); beach profiles were surveyed along the dashed lines: (a) 26 August 1981; (b) 11 August 1982; (c) 15 August 1983.

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

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.

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

TABLE 2. Surface oil cover changes: 1981-83

Year	Total oiled area (m²)	Oil distribution by class (m²)			
		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 (m²)	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 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·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.

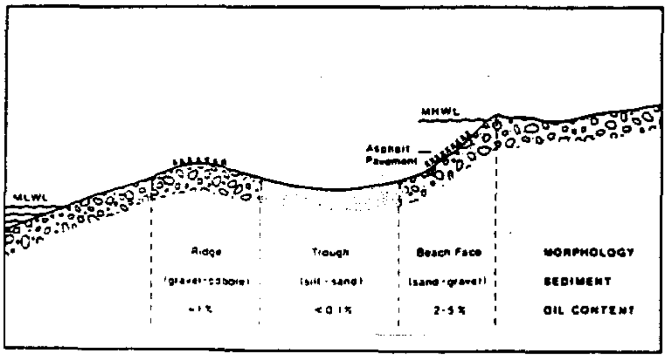

FIG. 4 Schematic of relationship between beach morphology, sediment type and surface oil concentrations (% oil in sediment by weight) in August 1983 along Profile 5 (Fig. 2c).

TABLE 4. Intertidal total extractable hydrocarbons (oil in sediment by weight: mg·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·kg⁻¹)	Surface oil volume	
			100%EA method	Volume method
19 Aug 1981	6	17400	<5.3 m³>	5.3 m³
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 1983ᵃ	9	11900	—	1.6
16 Aug 1983ᵇ	10	4800	—	0.6
16 Aug 1983ᶜ	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)

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, Augu 1983

	Area (m^2)	Mean total hydrocarbon concentration ($mg \cdot kg^{-1}$)	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 immediatel after the Bay 11 oil release and subsequent stranding, largel due to evaporation of lower molecular weight saturated an aromatic hydrocarbons (Figs. 6 and 7). The stranded oil sam

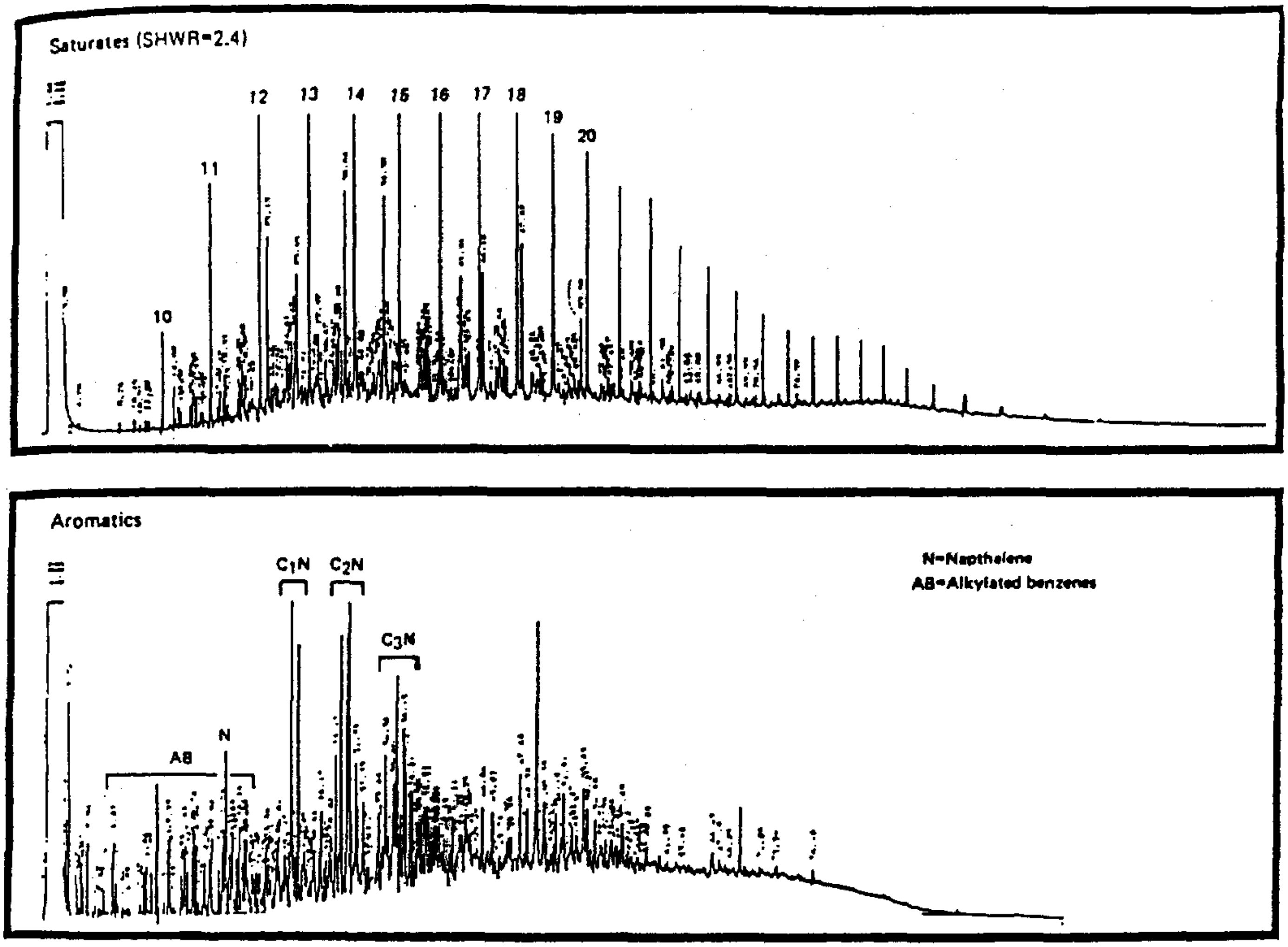

FIG. 6. GC^2 profiles of beached oil from Bay 11 one day after stranding.

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

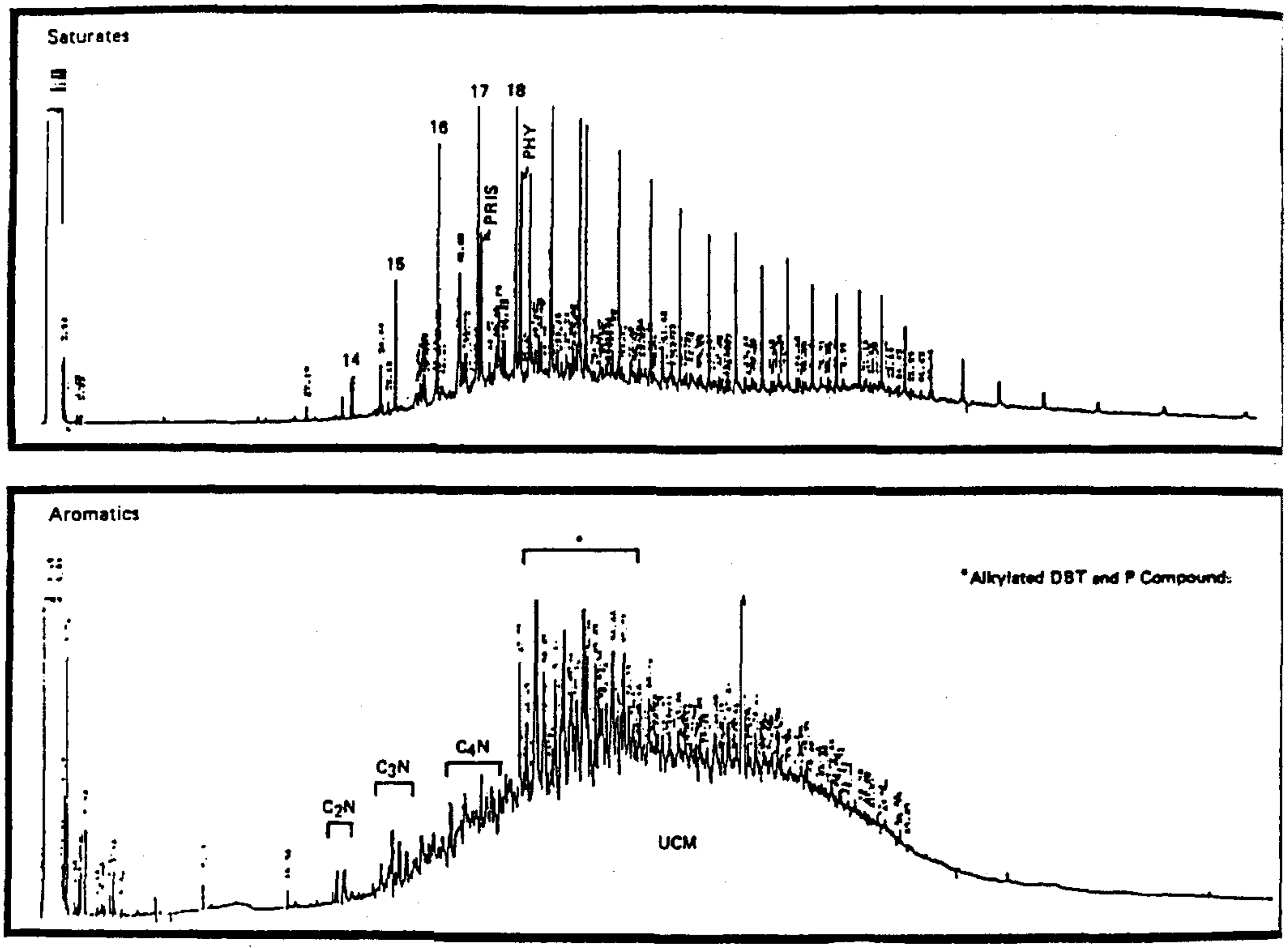

FIG. 7. GC^2 profiles of beached oil from Bay 11 one month after stranding.

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 o spilled oil, other than at a very general scale, or to produce dat sets that permit estimation of the changes in the volume o stranded oil through time.

Following the *Arrow* oil spill in Chedabucto Bay in 1970, tw samples were collected from an asphalt pavement at Arichat Nova Scotia, three months after the oil was stranded. Analysi of these samples produced values of 40 000 and 50 000 mg·kg^{-} (Owens, 1971). That asphalt pavement was subsequentl removed by heavy equipment so that no further data wer available from this site. Visual observations three years after th same spill, at Black Duck Cove and at Crichton Island, Nov Scotia, indicated the presence of asphalt pavements (Owens 1978). Sediment samples were collected at that time fro different intertidal locations, and Rashid (1974) noted that th samples from the low-energy environment were relativel unweathered in comparison with the original oil. Vandermeule and Gordon (1976) show that after five years the amounts of oi in pavement samples in this area were 11.6 ± 8% (wt·wt^{-1}) an that oil-in-sediment concentrations ranged from 6700 to 15 80 mg·kg^{-1}. Samples collected in the following year in the sam area produced oil-in-sediment concentrations up to 25 000 mg·kg (Thomas, 1977).

Large asphalt pavements were formed following the *Metul*

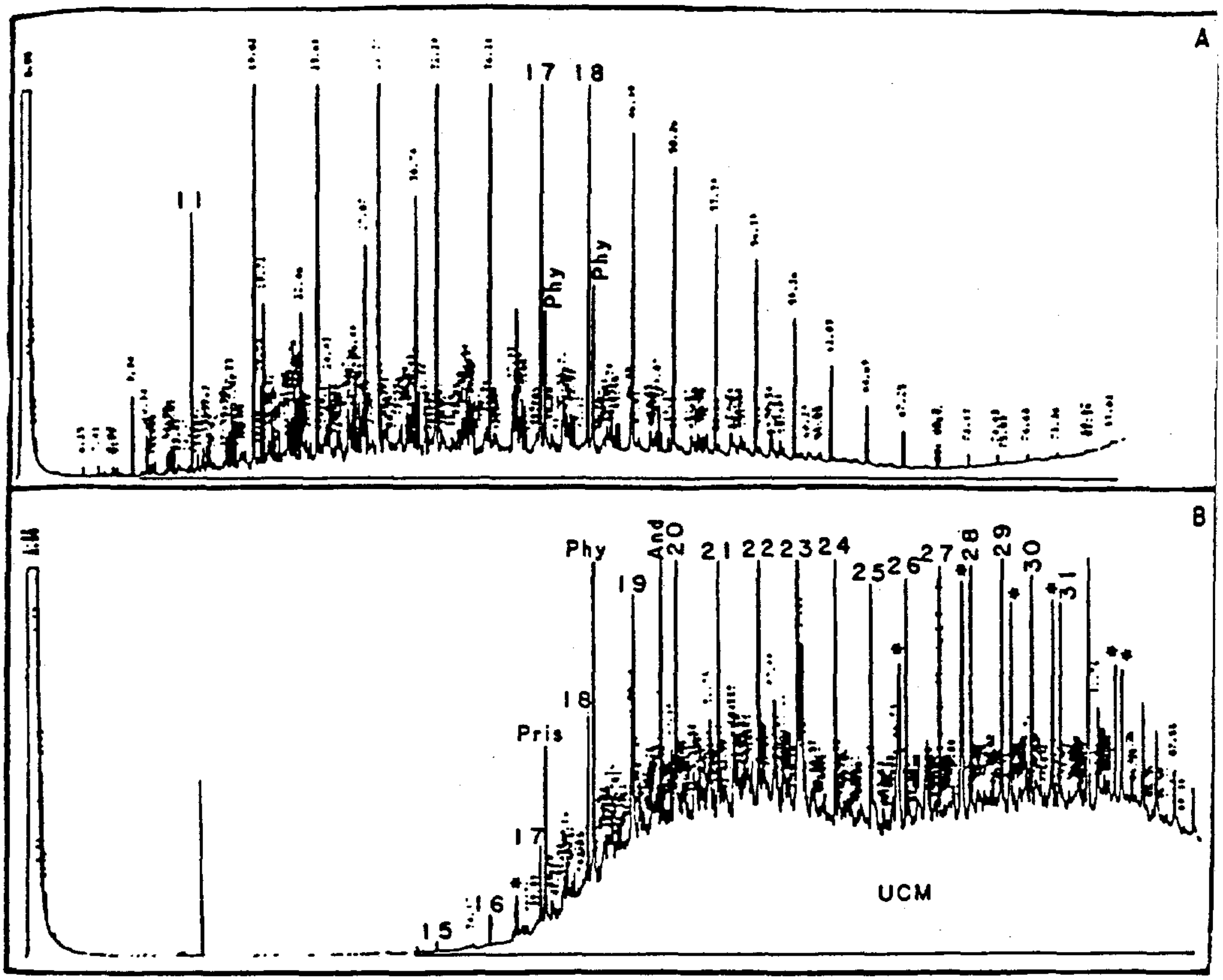

FIG. 8. GC^2 trace of Bay 11 beach sediments; showing undegraded, unweathered oil (A) and weathered and degraded oil (B) two years after stranding.

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·kg^{-1} oil in sediment concentrations, with half of the values between 20 000 and 50 000 mg·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·kg^{-1} in the upper intertidal zone and 147 mg·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 an increase in the total hydrocarbon concentrations found in t adjacent subtidal sediments (Boehm *et al.*, 1984). Sampl analyzed in 1982 yielded values in the range of 2-10 ppm, wi the highest values (up to 70 ppm) located adjacent to Profile 6 water depths of 3 and 7 m. The analytical results from 19 (Table 11) show a sixfold increase in the total hydrocarb concentrations in the subtidal sediments of this area, as com pared to the results of analyses conducted on samples collect in 1981 (Boehm *et al.*, 1982). The highest concentrations we again in the vicinity of Profile 6 in the area between the 3 and m depth contours. As previously noted, geochemical analysis the subtidal samples indicates that the oils sampled in subtidal sediments were biodegraded as a result of process that occurred when the oils were resident in the intertidal zo (Boehm *et al.*, 1985).

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

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

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

TABLE 11. Analytical results from subtidal sediment samples collect on a microbiology transect from the centre of Bay 11, 13 August 198

Station	Depth below LWL* (m)	Distance from LWL* (m)	Estimated petroleu concentration (mg·kg
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.

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Recolonization of Rocky Shores in Cornwall After Use of Toxic Dispersants to Clean Up the *Torrey Canyon* Spill[1]

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SOUTHWARD, A. J., AND E. C. SOUTHWARD. 1978. Recolonization of rocky shores in Cornwall after use of toxic dispersants to clean up the *Torrey Canyon* spill. J. Fish. Res. Board Can. 35: 682–706.

Fourteen thousand tons of Kuwait crude oil, reduced from 18 000 tons by weathering at sea, was stranded along 150 km of the coast of West Cornwall, England, in March 1967. The oil was treated with 10 000 tons of toxic dispersants during cleaning operations. By itself the oil was not very toxic, although it killed some limpets and barnacles, and most of the mortalities that followed cleaning were due to the dispersants. There was a graded effect. Most animals and some algae were killed on the shores treated heavily with dispersants, while a few animals and most algae survived in places less heavily treated. However, long stretches of coast were contaminated to some extent by drifting of patches of oil and dispersants along the shore and by indiscriminate dispersant use in remote coves. The general sequence of recolonization was similar to that which has been found after small-scale experiments, where the rocks were scraped clean, or where limpets were removed, but took longer to complete. There was first a rapid "greening" by the alga *Enteromorpha*; then a heavy settlement and growth of perennial brown algae (*Fucus* species), leading to loss of surviving barnacles. A settlement of limpets and other grazing animals followed, with eventual removal or loss of the brown algae. The final phases were a reduction in the limpet population and a resettlement of barnacles. Lightly oiled, wave-beaten rocks that received light dispersant treatment showed the most complete return to normal, taking about 5–8 yr; heavily oiled places that received repeated application of dispersants have taken 9–10 yr and may not be completely normal yet. Most common species returned within 10 yr, but one rare hermit crab is still missing from places directly treated with dispersants. The early recolonization by algae resulted in a raising of the upper limit of *Laminaria digitata* and *Himanthalia elongata* by as much as 2 m in wave-beaten places, demonstrating that grazing pressure by limpets must be one of the factors controlling the zonation of these plants. Later, other species of plants and animals were found higher up the shore than usual, under the shade and shelter provided by the dense canopy of *Fucus*. Fluctuations in the populations of algae and herbivorous animals during the course of the recolonization illustrate the importance of biological interactions in controlling the structure of intertidal communities. Pollution disturbance affects the herbivores more than plants, hence the point of stability of the community is shifted towards the sheltered shore condition of low species richness and greater biomass.

Key words: petroleum, dispersant, rocky shore, *Torrey Canyon*, recolonization, coastal ecology, pollution

SOUTHWARD, A. J., AND E. C. SOUTHWARD. 1978. Recolonization of rocky shores in Cornwall after use of toxic dispersants to clean up the *Torrey Canyon* spill. J. Fish. Res. Board Can. 35: 682–706.

Quatorze mille tonnes de pétrole brut de Koweït, provenant de 18 000 tonnes réduites par altération à l'air en mer, se sont échouées sur 150 km de côtes dans la partie ouest de Cornouailles, Angleterre, en mars 1967. Au cours des opérations de nettoyage, le pétrole fut traité à 10 000 tonnes de dispersants toxiques. Le pétrole n'était pas par lui-même très toxique, bien qu'il causa la mort de quelques patelles et balanes. Les dispersants furent responsables de la plupart des mortalités qui suivirent le nettoyage. Il y eut effet progressif. Sur les rivages lourdement traités aux dispersants, la plupart des animaux et quelques algues furent tués, alors que, aux endroits moins lourdement traités, quelques animaux et la plupart des algues survécurent. Cependant, de longs segments de la côte furent plus ou moins contaminés par la dérive de pétrole et de dispersants le long du

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rivage et par l'emploi à tort et à travers de dispersants dans des anses éloignées. La recolonisation se fit en général suivant le même ordre que celui qui avait été observé dans des expériences à petite échelle dans lesquelles des rochers avaient été nettoyés et les patelles enlevées. Elle se fit toutefois plus lentement. Il y eut d'abord un « verdissement » rapide par l'algue *Enteromorpha*; ensuite une abondante colonisation et rapide croissance d'algues brunes vivaces (espèces de *Fucus*), entraînant une perte de balanes qui avaient survécu. Vint ensuite une colonisation de patelles et autres brouteurs, causant éventuellement l'enlèvement ou la perte des algues brunes. Les phases finales comportèrent une réduction de la population de patelles et une nouvelle colonisation de balanes. Les rochers battus par les vagues et légèrement touchés par le pétrole, qui ne reçurent qu'un léger traitement aux dispersants, sont ceux qui retournèrent le plus près de la normale, après environ 5 à 8 ans; les endroits fortement touchés par le pétrole et qui reçurent une application répétée de dispersants prirent 9 à 10 ans à se rétablir et ne sont peut-être pas encore revenus à la normale. La plupart des espèces communes étaient revenues en dedans de 10 ans, mais un Bernard l'Ermite rare manque encore aux endroits directement traité aux dispersants. Comme conséquence de la recolonisation par les algues, la limite supérieure de *Laminaria digitata* et d'*Himanthalia elongata* s'est élevée d'une distance allant jusqu'à 2 m aux endroits battus par les vagues, ce qui démontre que le broutage par les patelles doit être un des facteurs contrôlant la répartition en zones de ces plantes. Plus tard, on a trouvé des espèces de plantes et d'animaux à un niveau plus élevé que d'habitude sur le rivage, profitant de l'ombre et de l'abri fournis par de denses tapis de *Fucus*. Les fluctuations que subissent les populations d'algues et d'animaux herbivores au cours de la recolonisation démontrent bien l'importance des interactions biologiques dans le contrôle de la structure des communautés intertidales. La perturbation causée par la pollution affecte les herbivores plus que les plantes. Il en découle que le point d'équilibre de la communauté se déplace vers une condition abritée des rivages, à faible diversité d'espèces et abondante biomasse.

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THE staff of the Marine Biological Association (Smith 1968) have described the immediate consequences of the release of 119 000 tons of Kuwait crude oil from the tanker *Torrey Canyon* which grounded on the Seven Stones reef off the western tip of Cornwall in 1967; the report was compiled and published within a year of the disaster, and little could be said about recolonization of denuded shores or long-term changes in the ecosystem. Later accounts of the situation in Brittany (Bone and Holme 1968; Stebbings 1970) and at Porthleven (Bryan 1969) described events up to 18 mo after the spill, but were also unable to deal with long-term changes. More recent information has been reported at oil pollution symposia and in general reviews (Nelson-Smith 1968, 1972; Spooner 1970, 1971; Crapp 1971d). To balance gloomy forecasts of eco-disaster made in 1967, attention was drawn to the rapidity of the start of recolonization. Unfortunately, the use of the term "recovery" seems to have encouraged later writers to believe that all was now normal on Cornish shores: e.g. "recolonisation by animals from unpolluted cases . . . began almost at once, slowly at first but then more rapidly. By the time of the Santa Barbara oil spill (i.e. February 1969), recovery of most of the polluted areas seemed essentially complete" (Steinhart and Steinhart 1972); "considering the remarkably short period used up in recovery . . . of the natural communities" (Mackin 1973); "the damage was almost completely restored in one year, and returned to normal after a few more" (Wardley Smith 1976). "with exception ("Tampico Maru" spill) intertidal communities appear to have been affected least and to have recovered the fastest . . . usually within two years" (Hyland and Schneider 1976). These authors overlooked a serious contribution by Cowell et al. (1972) who "expected recovery to be very protracted," as indeed it has been in Cornwall.

Now, after 10 yr the affected shores in West Cornwall have achieved some degree of normality, which is what we understand by the word "recovery." Hence it is at last possible to give an account of the recolonization of the intertidal zone. In this contribution we describe some of the broad-scale changes observed on rocky shores and relate them to more detailed studies of fluctuations in population abundance of barnacles, limpets, and other common organisms at selected stations. Some additional data are given on the fate of the oil, and of events in other habitats, derived from information kindly supplied by colleagues.

Taxonomy is based on the Plymouth Marine Fauna (Marine Biological Association 1957) and on Parke and Dixon (1976); authors' names and references to species are quoted only where a different usage is employed. It has been impossible to name the encrusting coralline algae; they are referred to here collectively as "lithothamnia," as in general works on intertidal ecology.

The Oil and the Dispersants

The amount of oil released by the *Torrey Canyon* spill has not been exceeded since, though it was almost equalled by the *Urquiola* disaster at La Coruna in 1976 (Quiroga 1976). About half of the cargo did not reach the shore, and was sunk at sea after weathering or was dispersed by natural agencies (Table 1, Fig. 1), but

TABLE 1. Chronology of the *Torrey Canyon* oil spill.

Mar. 18, 1967	*Torrey Canyon*, carrying 119 000 tons Kuwait crude oil (S.G. 0.869) stranded on Seven Stones reef.
Mar. 20, 1967	31 000 tons of oil released up to this date, some treated at sea with dispersants (68 000 dm³).
Mar. 25, 1967	First oil came ashore in Cornwall.
Mar. 26, 1967	Cumulative total of 49 000 tons of oil released from wreck; the last 18 000 tons went towards Cornwall and lost 4000 tons by evaporation of the lighter fractions.
Mar. 26–28, 1967	40 000–50 000 tons more oil released as ship breaks up; most of it never reached the shore and was ultimately sunk or weathered in the Bay of Biscay.
Mar. 28, 1967	By this date an estimated 14 000 tons of oil had come ashore in West Cornwall; 10 000 tons of dispersants were used to clean it up.
Apr. 6–11, 1967	The oil released up to March 20 now came ashore in the Channel Islands and North Brittany, an estimated 20 000 tons after evaporation.
May 19–20, 1967	A small quantity of the oil (300 tons) released from the wreck in the period March 26–28 now came ashore in West Brittany; the rest was sunk by treatment with stearated chalk, or was lost in the North Atlantic ocean.

some 40 000 tons is still believed to have come ashore in Cornwall, Brittany, and the Channel Islands (Smith 1968; Cabioch 1971). What distinguishes the affair from many other oil spills is not the quantity of oil that came ashore, but the quantity of dispersants (referred to as "detergents" at the time) used to remove oil from the beaches and rocky shores. There were undoubted instances of organisms being killed or damaged by the oil alone (O'Sullivan and Richardson 1967), but the relatively low toxicity of the oil is believed to have been further reduced by evaporation of the lighter and aromatic constituents during the interval of 1 wk or more between release and stranding (Smith 1968; Corner et al. 1968; but cf. Spooner 1971). Thus, although a little oil has persisted for some years, most of the effects observed on Cornish shores are due to short massive kills by dispersants applied in the spring months of 1967.

PERSISTENCE OF THE OIL

A small quantity of the *Torrey Canyon* oil remained on the Cornish coast after dispersant application ceased, and a larger quantity was left on the shore in Guernsey and Brittany when cleaning operations ended there.

On dispersant-treated shores a little oil often remained on the rocks for some months, as for example at Porthleven and Trevone, but this weathered as fast as t apparently untreated oil at Godrevy Point and little w left after 1 yr. In contrast, oil driven into beach sa by dispersant treatment, buried by bulldozing, or co ered by natural sand movements, persisted for sever years. In 1968, oil was surfacing at Whitesands, Senne between mean tide level (MTL) and high water nea (MHWN) causing iridescent streaks; and in the harb at Porthleven, greater quantities of oil were found 5 cm deep, easily revealed by turning over large stone Both of these superficial oil seepages disappeared b 1976. In a small area at Watergate Bay, on the nort coast of Cornwall (between station 9 and Trevone o map, Fig. 2), weathered oil was uncovered by natur beach movements in 1970, having undergone very littl biological degradation (Spooner 1971); the same o was exposed again in 1971 and 1972 (Spooner persona communication). A smaller trace of oil was found o St. Ives in 1971, on dead shells of *Ensis* buried 15 c down in the sandy bottom at 10 m depth of wat (Forster personal communication). In view of the resistance of crude oil to degradation once it has sunk belo the fully oxygenated layer in the sand (Johnstone 1970 it is likely that traces still remain today on the Corni coast, buried in the sands and the immediate sublittora

Untreated oil survived for over a year on north Brittany shores, on high water rocks, sands and salt marshe but considerable weathering occurred in this time (Bo and Holme 1968; Stebbings 1970). Similar patches o oil survived several years on some partly sheltered hig water rocks on the west coast of Guernsey, but th amount still present in 1971, the last year photographed was very small, the bulk of it having weathered awa (Forster and Swinfen personal communication).

In the estuary at Hayle (between 11 and 12 on ma Fig. 2), which was not treated with dispersants (Smi 1968), a thin coating of oil on a sea wall had disappeared by 1969; in contrast, in a very sheltered regi at the head of the creek, at extreme high water spri tide level, there were still patches of well-weathere asphalt-like oil 1 cm thick in 1970 (Spooner person communication).

All of these examples of persistent *Torrey Cany* oil represent a very small fraction of the original, not a all comparable with the amounts that have persiste after other oil spills.

THE DISPERSANTS AND THEIR EFFECTS

The technique for dispersing oil patches on the sho by treatment with high aromatic solvents containing nonionic surfactant, followed by hosing down, was developed by physicists at the Warren Springs Laborator England (Wardley Smith 1962). Tests at the MAF Fishery Laboratories showed that the mixture could toxic to shellfish, but it was felt that rapid dilution in th sea after application would prevent any damage to demersal or pelagic fish. The dispersing agents were therefore approved for use except in the vicinity of shellfi

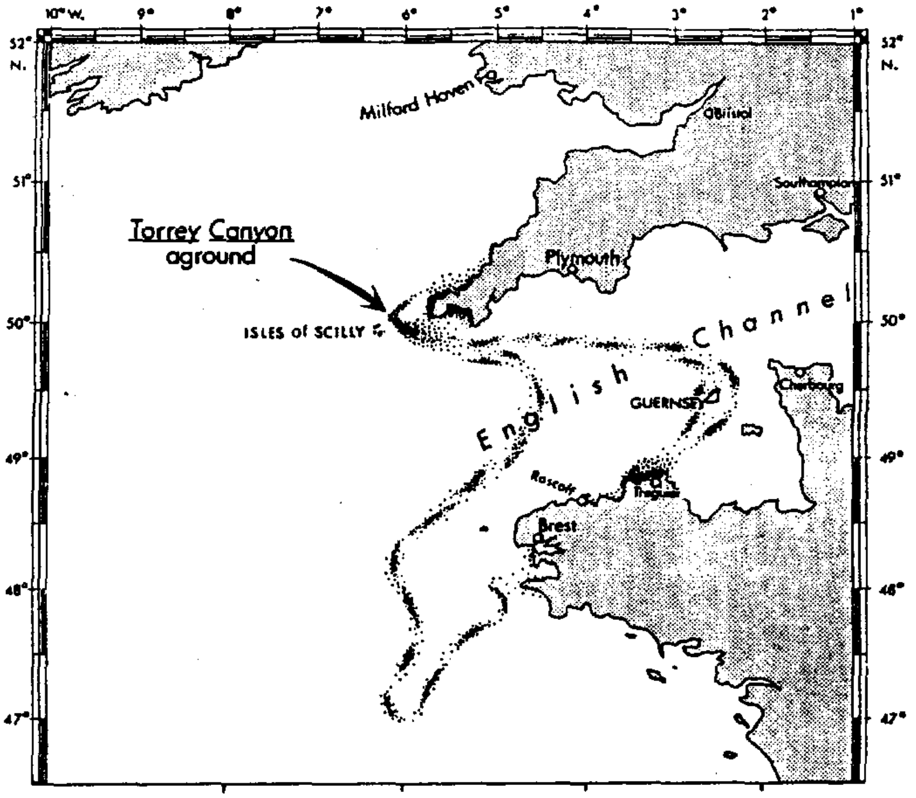

FIG. 1. Approximate track of the oil from the *Torrey Canyon*, and the places where it came ashore; *see also* Table 1. *Reproduced by permission of the Marine Biological Association from Smith* (1968).

eds, *and their application became official policy.* Unfortunately the results of the toxicity tests were distributed only in mimeographed reports, and not published until after the *Torrey Canyon* cleaning was over (Simpson 1968; Portmann and Connor 1968). In the emergency few people were informed of the toxicity of the dispersants to all forms of life, and indeed some of the spraying was carried out without enough regard for the safety of the operators themselves (cf. instructions in Warren Springs Laboratory, 1963 with those in Wardley Smith 1968). Scientific and public concern at the widespread use of dispersants was therefore directed at the surfactant component, initially based on published *reports of experiments* with freshwater life (e.g. Marchetti 1965). The extreme toxicity of the dispersants to marine life soon became apparent through field observations and hastily arranged laboratory tests. Today there is much published information on this point of which we were then ignorant (Boney 1968; Baker 1971; Crapp 1971b, d; Ottway 1971; Portmann 1972; Brown 1973; Beynon and Cowell 1974; van Gelder Ottway 1976). The most commonly used dispersant during the *Torrey Canyon* clean up contained 12% nonionic surfactant and 3% *stabilizer in a high aromatic solvent* ("kerosene extract"). The mixture was shown to have a 24-h LC_{50} varying from 0.5 to 5 ppm on sublittoral *organisms, and from* 5 to 100 ppm on intertidal organisms. Over short periods the solvent was the most

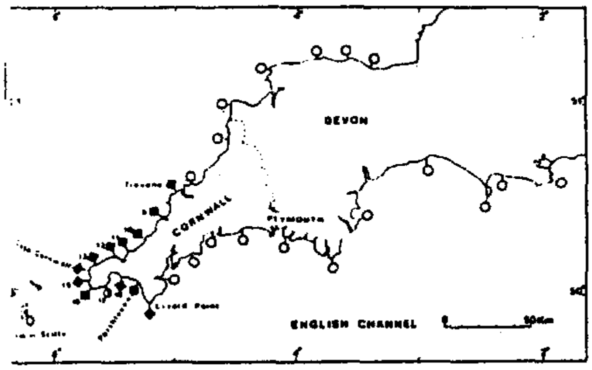

Fig. 2. Rocky shore stations investigated each year in outhwest Britain since 1955. Black rectangles, much affected by *Torrey Canyon operations; half* white circle, ightly affected; white circles, free of *Torrey Canyon* effects. umbers: 9, Newquay; 10, Chapel Porth; 11, Godrevy oint; 12, St. Ives: 13, Pendeen; 15, Sennen Cove; 16, orthgwrra; 17, Lamorna Cove and Mousehole; 18, arazion (Perranuthnoe is just to the east).

toxic component (Corner et al. 1968), but over long periods all components were very toxic (Wilson 1968). Most of the differences in sensitivity between species were fully supported by field observations, and the most sensitive common animals were the limpet *Patella vulgata* intertidally (5 ppm) and the razor shell *Ensis siliqua* sublittorally (0.5 ppm). The concentrations at which the dispersants were toxic to all life were very much lower than those required to emulsify the oil (1 part of dispersant to 2–4 parts of oil) and very much lower still than the ratio actually applied in the field (10 000 tons of dispersants to 14 000 tons of stranded oil).

The one redeeming feature of the dispersants, shown by laboratory testing, was the rapid loss of toxicity of the solvent fraction when exposed to the air, though the surfactant and stabilizer were more persistent (Corner et al. 1968; Wilson 1968). However, field studies depressingly confirmed the results of the laboratory tests, and showed that close to dispersant spraying practically all animal life was killed, while many algae, including members of the Chlorophyta, Rhodophyta, and Phaeophyta were killed or damaged. The herbivorous gastropods, the decapod crabs, and the echinoderms seemed to be the worst affected, and on places cleaned thoroughly hardly a living animal could be found. Thus on some rocky shores recolonization started from scratch; on others, treated less heavily, some fucoid algae, the more hardy animals such as barnacles, some sea anemones, the top-shell *Monodonta*, and occasionally a few limpets survived. There was thus a graded effect which would influence recovery, most severe on heavily treated shores close to tourist centers and especially around high water mark, and least severe on a few stretches of steep cliffs or along the outer edge of reef platforms at low tide level.

In theory, in view of the rapid decline in toxicity of the solvent component, recolonization of affected shores could have begun within a week or two of the last application of dispersants, and in fact settlement of the larvae of the barnacle *Balanus balanoides* was seen at some places early in May. However, rocky shores with easy access by road were treated several times, a few of them for up to 3 mo after the first oil came ashore. The characteristic aromatic smell of the dispersant could be detected at Trevone and Sennen Cove, for example, in June. In such places there was the danger that the repeated applications would not only bring the total kill to 100% (cf. Crapp 1971b, c) of all organisms, but would lead to accumulation of the persistent components such as the surfactants and the higher boiling point aromatics in the sandy beaches (cf. Blumer et al. 1970) and in sand and gravel under boulders or in crevices on rocky shores. This aspect has to be borne in mind when considering the slower course of recolonization on some sections of the shores.

A final problem caused by the widespread use of dispersants is that it has never been fully possible to separate the effects of oil alone from the effects of dispersants. Although many parts of the West Cornwall coast are either inaccessible or approached by roads unsuitable for heavy transport, dispersants were often carried by helicopter, and the opened drums simply rolled over the cliff (Brown 1972; Frost 1974). Discrete patches of oil–dispersants drifted alongshore with the tides and currents (Smith 1968) ensuring that intermediate stretches were also affected. At one time we thought that the short length of coast from Lamorna Cove to Mousehole would form a satisfactory control but even here some oil came ashore late in the spill and was treated with dispersants (Bellamy et al. 1967). It is thus incorrect to refer in general to "recolonisation from unpolluted oases" when continuous lengths of coast were affected to some degree, and when many of the returning organisms had to travel considerable distances.

Recolonization of a shore can occur in four ways: (a) by migration of adults of mobile species from unaffected areas (cf. Dauer and Simon 1976); (b) by direct settlement of planktonic spores or larvae liberated by breeding organisms in unaffected areas; (c) migration of juvenile stages of species with direct development (i.e. without planktonic larvae); (d) rafting of adults or their egg masses attached to floating seaweed or debris. The first process, as we have mentioned, was hampered by the lengths of coastline affected, as to some extent was the third, leaving the settlement of planktonic larvae and spores as the most likely initial stage of recolonization, with rafting as the next possibility. For planktonic stages much depends on life history, breeding season, and time elapsed between liberation and settlement. At temperatures experienced inshore in West Cornwall (annual range 8–16°C) limpet larvae take about 10 d from spawning to reach settlement stage, and barnacle larvae take about 20 d from hatching to settlement, hence possible travel distances of 30–50 km might be anticipated (cf. Crisp 1958). Distances of this order are within reach of the completely unharmed shores outside the damaged area of West Cornwall (Isles of Scilly to the west; beyond Trevone to the north; round the Lizard peninsula to the east). For species without planktonic larvae such distances represent formidable barriers, and we have to look closer, for possible spread from places treated less heavily with dispersants or from islets and reefs off the coast outside the main drift of dispersants.

The General Course of Recolonization on Rocky Shores

Figure 2 shows the stations in southwest Britain that have been visited annually since 1955 to follow natural changes in selected intertidal animals, chiefly the barnacles (e.g. Southward 1967); records for some of the stations go back to the 1930s (Fischer-Piette 1936). Not one of the stations in the *Torrey Canyon* area escaped some damage due to oil or dispersants. We have selected certain of them to follow details of recoloniz

TABLE 2. The time course of recolonization of rocky shores in Cornwall, expressed in years from the date of the *Torrey Canyon* disaster, March 1967

	Lizard Pt. exposed (Vellan Drang)	Lizard Pt. sheltered (Polpeor Cove)	Porthleven, west of harbor	Maen Du Pt., Perranuthnoe	Sennen Cove exposed (300 m east of pier)	Sennen Cove (near Pier)	Cape Cornwall (Porthledden side)	Trevone, exposed ("sewer rocks")	Trevone, sheltered (MTL reefs)
Relative exposure to wave action	+++	++	++	++	+++	++	+++	+++	+
Amount of oil stranded	+	++	+++	+	++	+++	++	++	+++
Dispersant treatment	(+)	+++	+++	(++)	++	+++	++	++	+++
Enteromorpha maximum[a]	1	1	1	1	0–1	1	1	0–1	1
Maximum *Fucus* cover	2–3	1–3	1–3	2–3	1–3	1–3	1–2	2	1–3
Minimum of barnacles	2	2	3	4	3	3	3	2	2–6
Maximum numbers of *Patella*	—[b]	6	5	5	—[b]	3	3	3	5
Fucus vesiculosus starts to decline	4	4	4	4	4	5	3	3	4
Fucus vesiculosus all gone	5	6–7	6–7	6	5	6	5	5	8
Increase in barnacles	4	6	6	5	4	6	4	3	7
Numbers of *Patella* reduced	—[b]	6	8	7	6–7	8	7	—[b]	6
Normal richness of species regained	5	9	10[c]	8–10	9	9	8–9	5–6	9–10[c]

[a] Only Trevone could be visited often enough from Plymouth to be sure of the extent of the 'greening' the 1st yr.
[b] No quantitative data.
[c] Full richness of species probably not yet regained on the area surveyed.
( ) Dispersant treatment comparatively lighter than at other places given same score.

ation, and the sequence of events is summarized in Table 2. Our data are partly in the form of field notes, including counts of the commoner animals on quadrats of 1 × 1 dm and 1 × 1 m, and partly in the form of color transparencies. It is impossible to overemphasize the importance of good color photographs, including close-ups, in following changes of this nature.

The first opportunists to return were the green algae *Enteromorpha* and *Ulva*, seen during June and becoming very obvious through the summer and autumn. This "green flush" is by now well known to follow severe oil pollution or dispersant application on temperate zone shores (Bellamy et al. 1967; Smith 1968; Nelson-Smith 1968, 1972; Crapp 1971b, d, f; Baker 1976a, b). It is principally a sign that the grazing herbivores, such as limpets, top-shells, and winkles, are absent or greatly reduced in number. This can happen naturally on a small scale due to storms, changes in sand levels, scouring by sand and gravel, or excessive freshwater run-off. It may also be caused by pollution other than oil (Smyth 1968), in which case we must distinguish it from "greening" due to eutrophication, for which *Ulva* rather than *Enteromorpha* is the best indicator (Burrows 1971). The continuance of "greening" is dependent not only on absence of herbivores but on the facility for rapid reproduction possessed by these relatively simple plants whose gametes and spores show peaks of abundance related to spring tides (Christie and Evans 1962; Rhyne 1973; see also Knight and Parke 1931). On some shores, e.g. Trevone and Sennen Cove, the green algae did not immediately recolonize the inner sheltered parts of the reefs, which showed maximum "greening" the next year. It is conceivable that this delay was due to persistent traces of dispersants adsorbed into gravel and sand under boulders or in silt in crevices in a concentration sufficient to damage the motile spores or gametes which resemble unicellular algae and may have a similar low resistance to toxins (cf. Smith 1968; Vandermeulen and Ahern 1976).

During the late summer and autumn of 1967 the large brown algae *F. vesiculosus* and *F. serratus* began to succeed the green algae. The first of these species exists in at least two forms or varieties in northwest Europe. In sheltered places the plants are large and carry air bladders (vesicles) along the fronds. In wave-beaten places, where limpets and barnacles are abundant, the plants are much smaller, without air bladders, and are usually referred to as f. *linearis* (= *evesiculosus*) (Lewis 1964; Boney 1966). From December 1967 through the spring of 1968 the outer parts of the reefs were browned by dense growths of f. *linearis*, while in less damaged sheltered shores f. *vesiculosus* also flourished (Fig. 4, 5, 6; Fig. 16, 17). This succession of the "green flush" by fucoids is also well established now for oil-polluted temperate shores after dispersant treatment (e.g. Crapp 1971b; Nelson-Smith 1972; Baker 1976b). However, places where greening was late or prolonged to the second spring usually failed to develop a growth of *F. vesiculosus* during the 1st yr. It is not certain if this was due to the absence of *Entero-*

morpha which provides protection from dessication at a critical stage in spore development after settlement (Knight and Parke 1950) or if residual dispersant toxicity might have remained long enough to inhibit settlement of spores during the summer fruiting season.

Under the dense mat of green and brown algae covering the affected shores in 1968 animal life was much reduced compared with that existing before the disaster. A few limpets had survived in places, and the cleared patches they maintained in the *Enteromorpha* by browsing allowed some barnacle settlement, but otherwise the barnacles that had survived the cleaning operations were gradually overgrown by the *Enteromorpha* and *Fucus* and eventually died. We do not know exactly why barnacles cannot live under a canopy of *Fucus*. It may be due to screening from the planktonic organisms on which the barnacles feed (Moore 1934), or physical effects such as abrasion of the young stages by the algal fronds when they are moved about by waves (Menge 1976). Another possibility is that the shelter and shade provided by the algae might allow the dog-whelk *Nucella* to feed on the barnacles for a longer period at low tide, and it is significant that barnacles can occur in quite high densities under *Ascophyllum* and *Fucus* in parts of estuaries where *Nucella* is absent or less common (cf. Moore 1934).

The few limpets that had survived on the cleansed shores grew much faster than normal on the abundance of algal food provided, up to 10 times faster than usual, and during 1968 they were joined by an equally fast growing number of juvenile *Patella* which had settled at low tide level or in wet places during the winter (Fischer-Piette 1941, 1948; Jones 1948; Lewis and Bowman 1975; Bowman and Lewis 1977) and were now moving up into the *Fucus* belt. The species of *Patella* found in Britain and NW Europe can feed on a much wider range of plants than is usual in other parts of the world or among species of the related genus *Acmaea* (Branch 1976). They normally browse on microscopic diatoms or other unicellular algae and larger encrusting species, rejecting only a few such as *Ralfsia* (Southward 1964), but when the opportunity offers they will readily feed on large and small plants of *Fucus*. Smaller limpets, below 20 mm length can be found feeding on the fronds and stipes of the *Fucus*, but all sizes will gnaw away at the holdfast and lower part of the stipe, where their tooth-marks can easily be seen. When large numbers of limpets are present the grazing on *Fucus* becomes severe, and the stipes are cut through or weakened to the point where they are torn away by the waves (Jones 1948; Southward 1956).

The first settlement of *Patella* on the *Torrey Canyon* affected shores was locally abundant ($8-12/dm^2$) but the overall numbers were low, and so was their size, hence grazing was insufficient to prevent a further heavy settlement of *Fucus* during the summer and autumn of 1968 (Fig. 11). It was at this stage, spring and summer of 1968, that we observed striking changes in zonation levels.

A second and larger settlement of *Patella* occurred during the winter of 1968–69, but the still increasing growth of the *Fucus* canopy prevented return of the barnacles, which reached their minimum in the years 1969 and 1970. The now rapid increase in limpet numbers and biomass (Fig. 12) restricted further settlement of *Fucus* in 1969 and later years, so that from 1970 to 1972 there was a rapidly ageing and thinning canopy of *Fucus* providing food for a quickly growing population of limpets underneath. From 1972 to 1974 most shores began to lose the *Fucus* dominance as the limpets removed or weakened the plants, and the last shores became "bare" in 1975.

In the absence of large algae the now enormous population of big limpets was reduced to feeding on microscopic and encrusting plants again, and there was not enough food to sustain them all. Many of them reacted by departing from their semisedentary ways (cf. Aitken 1962) and formed huge migrating "fronts" which worked their way across the reefs (Fig. 7) attacking the last remaining clumps of *F. vesiculosus*, and then gathering close to *F. serratus* persisting in pools and wet places (Fig. 14). Others, less adaptable, seem to have died or fallen easy prey to predators, and dead shells were washed up on some beaches during the winter of 1972–73. The typical limpet "fronts" were first seen at Porthleven in the winter of 1971–72, advancing westward, but similar "fronts" developed elsewhere in 1972 and 1973. The remnants of the "fronts" can still be recognized in 1977, gathered round pools containing *F. serratus*, having undergone a thinning out and stabilization since 1975 (Fig. 14). After the passage of these "fronts" across the survey areas, the population of *Patella* became reduced and the barnacle numbers steadily increased. From 1975 barnacles were dominant on most rocks, and algal growths seemed much reduced compared with before the disaster; in bright spring sunlight in 1976 and 1977 the shores appeared brilliantly white (Fig. 6, 13, 17).

Although the "greening" by *Enteromorpha* extended over such long stretches of coast, we were still surprised by the extent of the succeeding fucoid settlements observed in 1968 and 1969. At Porthleven, for example, it could clearly be seen from the cliff top that the *Fucus* dominance spread nearly 3 km west, almost to Trewavas Head, yet the main dispersant treatment in 1967 extended only 750 m west (see Bryan 1969). Comparatively late increases in fucoid cover occurred at other lightly affected, stations where "greening" was not noticed in 1968, hence we have to raise the possibility that some of the increase in *Fucus* in Cornwall in 1968 and 1969 was a result of the heavy settlement the 1st year bringing about a local increase in spore production. From the results of *Patella* clearance in the Isle of Man (Burrows and Lodge 1950; Southward 1956) it was suspected that the high density of *Fucus* on the experimental strips may have produced such a local abundance of spores that the surrounding rocks were colonized to a greater extent than would otherwise have been p

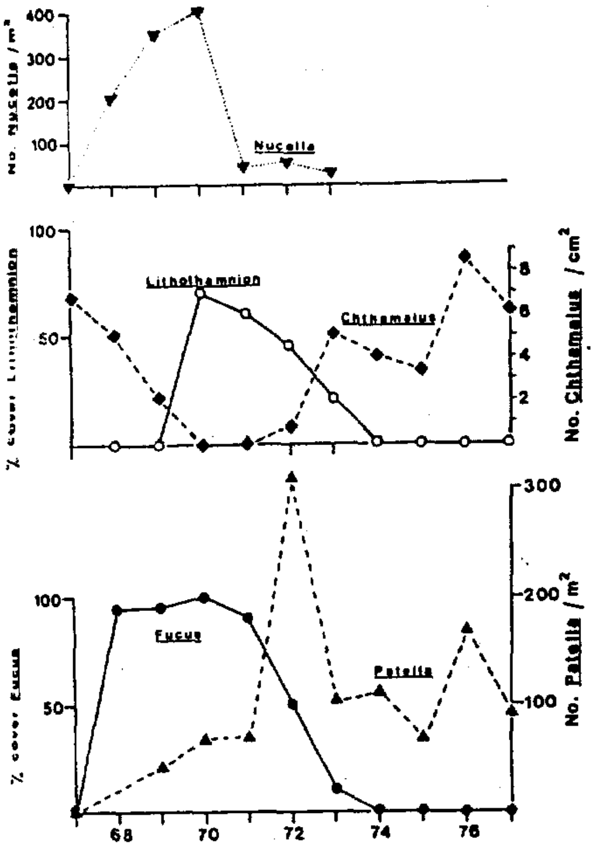

FIG. 3. Population fluctuations during recolonization on flat rocks at mean tide level at Porthleven from 1968 to 1977. Filled circles: percentage cover by *Fucus*. Filled triangles, no. of *Patella vulgata*/m²; open circles, percentage of rock covered by encrusting coralline algae ("lithothamnia"), filled rectangles, no. of barnacles (*Chthamalus*)/cm²; filled triangles and dotted line, no. of dog-whelks (*Nucella lapillus*) on a vertical surface near to the quadrats on which the other species were counted.

sible. If this happened in Cornwall, on the very much larger scale resulting from the disaster, it would help to explain the slower progress of the succession compared with the small experiments, and the longer period needed to regain stability.

OTHER HABITATS

The foregoing description refers to the rocky midlittoral or eulittoral zone as defined by Lewis (1964) and Stephenson and Stephenson (1972). It should be noted that the lichens of the supralittoral fringe were damaged by dispersants and were slow to return to normal (Brown 1972, 1973, 1974). More localized damage resulted in maritime terrestrial communities where dispersants were spilled on the cliff tops during cleaning operations, and these have been equally slow to recover (Frost 1974).

The immediate sublittoral zone suffered drastic mortalities close to places where large quantities of dispersants were used (e.g. Porthleven, St. Ives), but recolonization by mobile fish and crustaceans was reported within a few months (Drew et al. 1967). The infauna of such sublittoral areas was slower to return (Forster personal communication), having to wait for favorable settlements of larvae, and the first repopulation by the heart-urchin *Echinocardium* was noticed 2 yr later. The razor-shell *Ensis* was slower to return, even though some migration by adults seems to have happened, and the last observations, in 1971, suggest the population was not as abundant as would normally be expected.

We have very little information on sandy beaches other than that reported in Smith (1968). There were no previous published data on the meiofauna of the coarse sand beaches affected by dispersants in West Cornwall, but mortalities are believed to have been heavy, and the beach structure was temporarily changed by dispersant treatment. Judging from laboratory experiments (Johnstone 1970; Bleakley and Boaden 1974) recolonization may have been slow.

Effect of Wave Action and Varied Dispersant Treatment on Recolonization

A range of rocky shores was investigated in detail, and the results selected here illustrate how local circumstances may influence the course of recolonization.

PORTHLEVEN

The harbor region at Porthleven received very heavy dispersant treatment, and the rocks outside suffered from both direct treatment and drifting of partly diluted dispersant. The early course of recolonization by one species, the predatory gastropod *Nucella*, has been described by Bryan (1969), and we can now follow this through several more years. Some individuals at lower tide levels appear to have escaped the cleaning operations, and egg-cases were seen on the outer part of the reef at the end of April. By autumn 1967 a few adults with a shell showing "ledging," marks where growth was stopped for a while by dispersant effects, began to appear higher up the shore accompanied by larger numbers of juveniles which may have been survivors born before the disaster or may have hatched from the eggs seen in spring. These survivors and young specimens appear to have bred well, and by 1969 the population of *Nucella* was much larger than before the disaster (see Fig. 3); this may have been a result of lack of competition from other predators, or the shelter and shade provided by the growths of *Fucus*. In later years (Bryan personal communication, author's observations) the numbers of *Nucella* declined, perhaps as a result of the great reduction in the numbers of the barnacles on which they feed (Fig. 3).

As general recolonization of the inner parts of the

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FIG. 7. Porthleven, December 2, 1971, showing the "front" of *P. vulgata* "advancing" westwards towards the still dense growths of *Fucus* in the background.

reefs progressed, the area occupied by *Nucella* expanded. A single example was found near the harbor entrance (area d of Bryan 1969) early in 1970, and the species was found in somewhat greater number by the spring of 1973. This means that in the worst affected area, at least 34 mo were taken for recolonization, and by a species of considerable resistance to dispersants. In contrast, the decapod crabs which showed less resistance to dispersants, but which have planktonic larval stages and are more mobile in the adult stage, first began to return to the harbor area in November 1967, when they were found living under stones in the presence of persistent oil.

We have studied recolonization by several other species at Porthleven, mostly in the area of flat reefs at the most southerly point (area a of Bryan 1969). Quadrats were photographed and sampled annually each spring, and additional information on breeding of *Patella* was derived from autumn samples taken closer to the harbor. Details of the main sequence of changes at MTL are shown in Fig. 3 and some points illustrated in Fig. 4, 5, 6. It can be seen that 2 yr after the establishment of the *Fucus* cover, barnacles had disappeared from the horizontal rocks at MTL, and there was a corresponding drop in numbers of *Nucella* found on vertical faces nearby. It is noteworthy that the shells of *Chthamalus* have a high content of organic matter (Barnes et al. 1976) and do not persist long on the rocks after death; by 1969 all signs of the barnacle mortality clearly seen in 1967 had vanished. The population of *Fucus* began to decline first near the harbor (area b of Bryan 1969) in 1971, a region of irregular rocks where grazing by *Patella* was reinforced by development of a big population of edible winkles, *Littorina littorea*. The "front" of *Patella* migrating from this area (Fig. 7) passed across the quadrat region in the spring of 1972 and coincided with the first drastic decline of the *Fucus* there. A major resettlement of barnacles followed in the autumn, and by 1974 the rocks were virtually without algae. From 1975 to date the barnacle population has continued to increase while the limpets have declined, but the algal growths at MTL and MHWN are less than observed before the disaster (Fig. 6).

At Porthleven most plants below MLWN survived the more diluted dispersants received at this level, though the limpets were killed. Considerable algal growths, including some "greening," occurred in the first 2 yr, but by 1972 the mean low water spring tide

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FIGURES 4, 5, and 6. Changes at Porthleven.

FIG. 4. May 8, 1967 after most of the oil had been removed by dispersants. The rocks look superficially normal, but in the absence of grazing molluscs, all killed, a film of diatoms and other small algae is beginning to darken the barnacle zone. Note the small tufts of *Fucus*, some of them now damaged but still illustrating the typical small-scale mosaic effect of the normal community on this shore. FIG. 5. May 12, 1968, a closer view of the southern corner of the rock outcrop seen in 4. Newly settled young plants of *Fucus vesiculosus* cover most of the rock, the remaining areas being bright green with *Enteromorpha* and *Ulva*. FIG. 6. May 18, 1977, the same viewpoint as 5, showing return to *Patella*/*Chthamalus* dominance. *Fucus* is now scarcer than before the disaster.

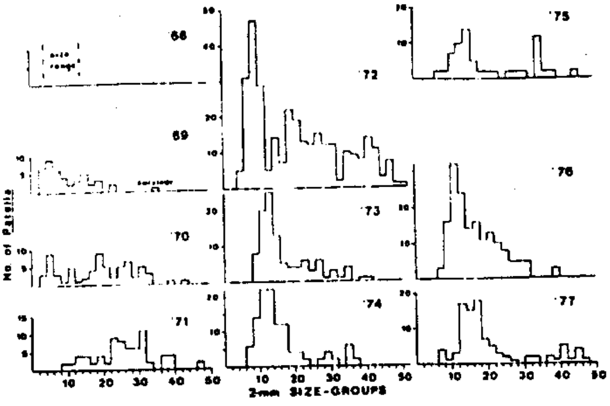


FIG. 8. Size-frequency histograms (in 2 mm shell length groups) for samples of *P. vulgata* from 1 × 1 m quadrats at mean tide level, Porthleven, from 1968 to 1977.

(LWS) region could be regarded as almost back to normal. In contrast, the HWS region took much longer to recover fully. Recolonization by *F. spiralis* did not reach a maximum until 1970, and these plants had not fully thinned out until 1975. The first littorinids to return were species with planktonic larvae, *L. neritoides* and small specimens of *L. littorea* (mistakenly identified as *L. saxatilis* in Smith 1968); these appeared late in 1967, but were more numerous by the spring of 1969. The smaller top-shell *Gibbula umbilicalis* also returned in large numbers (up to 24/m²) in 1969, and likewise has planktonic larvae. It was not until 1970 that species with direct development, other than *Nucella*, began to recolonize Porthleven, *L. littoralis* among the fucoids and a single genuine *L. rudis* Maton at the mean high water spring tide level (HWS). The first species is oviparous, and the eggs could have drifted in attached to seaweed; *L. rudis* is ovoviviparous (James 1968; Heller 1975), and the brood pouches contain developing embryos nearly all year round except in summer (Berry 1961; Bergerard 1971). The nearest population that is known to have survived is 4 km to the west, on a National Trust site that was lightly treated with dispersants. From 1968 to 1970 the HWS region carried a growth of *Enteromorpha* each spring, but with the return of all the littorinids and top-shells this greening disappeared. In 1971 *L. rudis* was present in slightly greater number, and by 1973 a local density of up to 6/dm² was found, and the harbor area had been recolonized. For some reason, the large top-shell *Monodonta* was slower to return than *G. umbilicalis*, though it also has planktonic larvae. A few escaped the cleaning operations and took up residence in crevices at HWN, but the flatter part of the reef was not recolonized until 1971, when small specimens were slightly more abundant on the rougher rocks to the east of the quadrat area. In 1972 the numbers increased to 6/m², and the species was abundant in 1973, when the numbers of *G. umbilicalis* began to fall.

Recolonization by the species of *Patella* was curiously local at Porthleven, and much influenced by microhabitat differences. On the MTL quadrats there was one possible survivor from before the disaster, but otherwise the population built up from new settlements each winter, starting in 1967–68 (see Fig. 8). The first new settlement reached 12–14 mm shell length by their second spring and up to 40 mm by the third spring, but really heavy settlement did not occur until the winter of 1970–71, by which time there was considerable bare rock below the lengthening and ageing *Fucus* plants. This last heavy settlement is seen as the modal class in spring 1972, accompanied by very large numbers of migrating adults. After this year the age-groups become increasingly confused by the slower rate of growth in the absence of algal cover, but the original settlements of 1967–68 and 1968–69 are still recognizable as small peaks on the size-frequency histograms at about 40 mm length. In 1977 these individuals would be 8 or 9 yr old, having grown very little during their last 5 yr. On many shores, as well as at Porthleven, this class forms the bulk of the remaining limpet "fronts" grouped near pools and wet places, and the shells show characteristic annual rings formed during the first few years when growth was rapid (cf. Fig. 14). During the years of *Fucus* cover all *Patella* shells showed signs of rapid growth in the protected and favorable habitat under the seaweed; they retained the protoconch, that relic of the larval twisted shell, for 2 yr or more, and although growth rings were present, the shell external surface was usually smooth and only slightly ribbed. Since the removal of the *Fucus* canopy the shells have become thicker and the erosion of the outer surface has brought the growth marks into greater prominence.

The most southerly distributed of the three species of limpet present on British shores, *P. depressa* Pennant (= *P. intermedia* Jeffreys), is a summer breeder (Orton and Southward 1961). New settlement was detected at Porthleven in the winter of 1967–68 but after 1969 this species was no longer found in the MTL quadrats dominated by *Fucus*. However, better settlements took place at MTL on some rather scoured rocks and concrete surfaces just outside the pier on the east side of Porthleven. The initial settlement of *P. vulgata* and *P. depressa* (240/m² by November 1968; 31% *P. depressa*) appears to have been great enough to prevent establishment of a general *Fucus* cover on these rocks. The mixed population received recruits in subsequent years up to 1972 when the sampling was discontinued; by this time the region was much nearer to normal than the main reefs to the west.

The third species of *Patella* in Britain, *P. aspera* Lamarck, is most characteristic of the lower half of the midlittoral zone on wave-beaten shores (cf. Lewis 1964). It was never abundant at the Porthleven stations except below MLWN, but a few specimens settled and grew at MTL on the flat reefs under the thinner cover of *Fucus* after 1970. These few large individuals were revealed on the quadrats when the *Fucus* disappeared but they themselves vanished after 1973, possibly mi

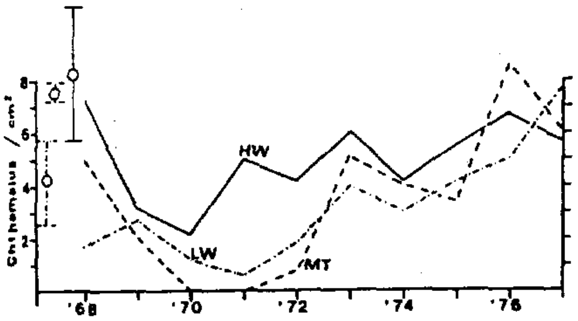


Fig. 9. Fluctuations in the numbers of *Chthamalus* at Porthleven from 1968 to 1977. Means and standard deviations are shown for counts in the years before the *Torrey Canyon* clean up. HW = mean high water neap tide level; MT = mid-tide level; LW = mean low water neap tide level.

migrating into nearby pools where they would find congenial conditions. The counts of barnacles at Porthleven show some interesting differences between tide-levels (Fig. 9). At both HWN and MTL they declined to a minimum density in 1970. The HW region began to be recolonized sooner, though numbers are still below the range of abundance found before the disaster. The MTL region under its cover of *Fucus* was much slower to improve, but the numbers of *Chthamalus* reached their former level by 1976. At first the LWN region appeared to be unharmed, but the population declined later to a minimum in 1971. It has since built up to much greater densities than experienced before 1967, possibly as a result of the competing algae being reduced by the larger numbers of *Patella*.

TREVONE

The extensive reefs at Trevone showed the maximum local differences in the time course of recolonization, in part related to intensity of dispersant treatment.

On the outer edge ("sewer rocks") not all the herbivores were killed, and just over 50% of the mussels and barnacles survived. However, there was an immediate "green flush" of *Enteromorpha* during the summer of 1967, though some settlements of *B. balanoides* and *Chthamalus* occurred. By 1968 the cover by *F. vesiculosus* f. *linearis* had increased and the barnacle population was reduced, but this change was quite short and the *Fucus* began to thin out in 1970, when barnacles and *Mytilus edulis* resettled in some number. Conditions were fairly normal by 1972–73.

In contrast, the partly sheltered MTL flat rocks half way out over the reefş have taken nearly twice as long to go through the cycle of recolonization. Some details are given in Fig. 10; it is noteworthy that the *Fucus* here consisted of very large plants of typical *F. vesiculosus*, with *F. serratus* among them (Fig. 11). The *Fucus* dominance lasted for 3 yr, and took a further 3 yr to disappear. As a consequence the barnacle zone on horizontal surfaces at MTL virtually vanished for 6 yr.

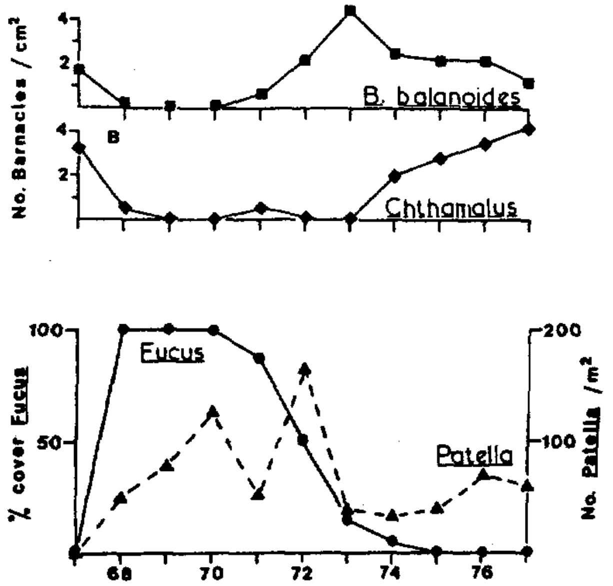
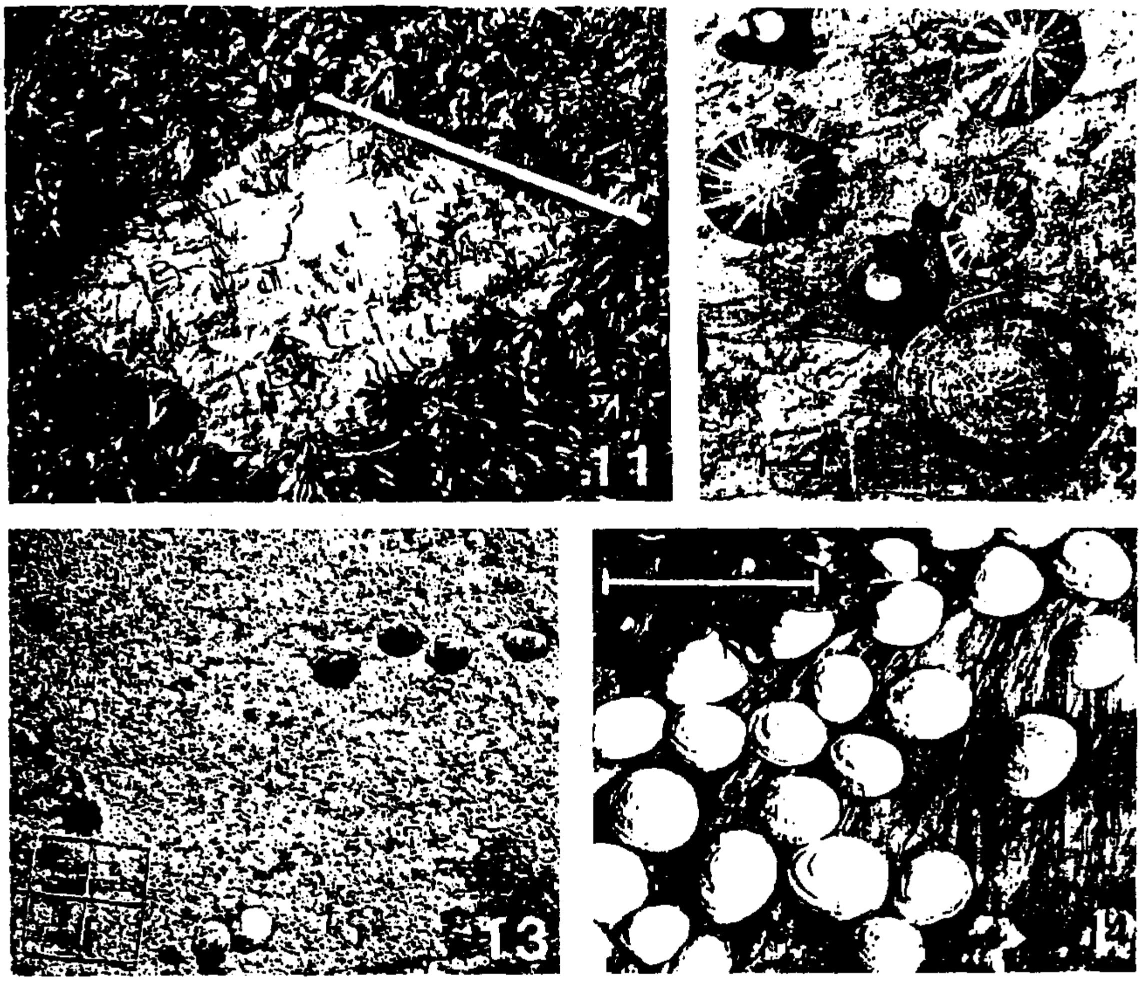


Fig. 10. Population fluctuations during recolonization of flat rocks at mean tide level at Trevone from 1968 to 1977. *Lower section*, circles indicate percentage cover by *Fucus*, triangles no. *P. vulgata*/m². *Upper section*, squares indicate no. *Balanus balanoides*/cm², diamonds no. *Chthamalus stellatus*/cm².

Patella vulgata never reached the same high numbers as at other stations, though its rate of growth appears to have been very fast (Fig. 12). In 1970 there had been a good settlement of *Spirorbis rupestris* under the *Fucus*, and *G. umbilicalis* had also returned. By the following year *G. umbilicalis* was present up to 40/m², and the *P. vulgata* had reached a maximum length of 50 mm, a remarkable size for 2½ yr growth. *Nucella lapillus* returned in 1969, but was more common in 1970; it may have been feeding on the numerous *Spirorbis* and the population of the low water barnacle *B. crenatus* which had now replaced the normal mixture of *Chthamalus* and *B. balanoides* previously present (Fig. 12). The first reduction of *Fucus*, in 1971, enabled *B. balanoides* to settle in some number, and it became the dominant barnacle for 3 yr (Fig. 10). The rocks were not really clear from *Fucus* until 1974, by which time the limpet population had fallen, and *Chthamalus* was then able to resettle (Fig. 13).

Of the limpets, only *P. vulgata* was present in the MTL quadrats during the first 5 yr at Trevone; *P. aspera* resettled in some numbers on the outer reefs in 1967–68 (up to 200/m², 9–23 mm length at MLWN in April 1968), but the southern species, *P. depressa*, was much slower to return than on the south coast of Cornwall, as for example at Porthleven and Perranuthnoe. The adult population in the southwest had been reduced by a succession of cold winters, and it is probable that the larval density in the plankton was lower along the north coast than on the warmer southern coast which carried more



FIGURES 11, 12, 13 AND 14. Fluctuations in algae and herbivores at Trevone.

FIG. 11. April 3, 1969. A metre quadrat has been cleared in the dense algal growths (20% *F. vesiculosus*, 80% *F. serratus*) just below mid-tide level. The rock under the algae is without barnacles, and the only fauna recorded was six small *P. vulgata*. Fig. 12. June 24, 1971. Close-up of part of a cleared quadrat at mid-tide level showing the rapidly grown *P. vulgata* now becoming abundant underneath the algal cover (90% *Fucus*). The rock surface carries many tubes of the worm *Spirorbis rupestris* and several *Balanus crenatus*, usually found only below low tide. Scale indicates 1 cm. Fig. 13. April 5, 1977, the same region photographed in 11 and 12, showing complete dominance of *P. vulgata* and mixed *Chthamalus*/*B. balanoides*. Wire frame is 10 × 10 cm. Fig. 14. April 24, 1975. An "aggregate" of old *P. vulgata* gathered at the edge of a shallow pool containing some plants of *F. serratus*. These limpets are survivors of the 1969 and 1970 settlements (as in 12), and now have rings on the shell showing how rapid was growth in the first 3 yr, and how little has taken place since. Scale indicates 10 cm.

breeding adults. A few did settle at Trevone in 1968 and later years, but we could find only $6/m^2$ at the most in 1971. However, by 1975 the numbers of *P. depressa* had slowly built up, and the former comparatively large size for this species of up to 45 mm had been regained, though at $24/m^2$ the abundance at the best station, an MLWN platform just inside the outer reefs, was less than in a previous period (Orton and Southward 1961). Further increases have followed, and this species is now present in small numbers over most of the rocks at Trevone.

One species that has not yet regained its former condition at Trevone is the long-lived brown alga *Ascoph lum nodosum*. In 1977 the surviving plants were o a tenth of the previous population existing at MLHW below Atlantic Terrace. *Ascophyllum* has been sho to be sensitive to oil and dispersants and is slow to r cover from cutting (Boney 1966, 1968; Keser et a 1977; Steele 1977). It may never recover from th combination of *Torrey Canyon* effects and increasing recreational use of this particular stretch of shore (cf Boalch and Jephson 1978).

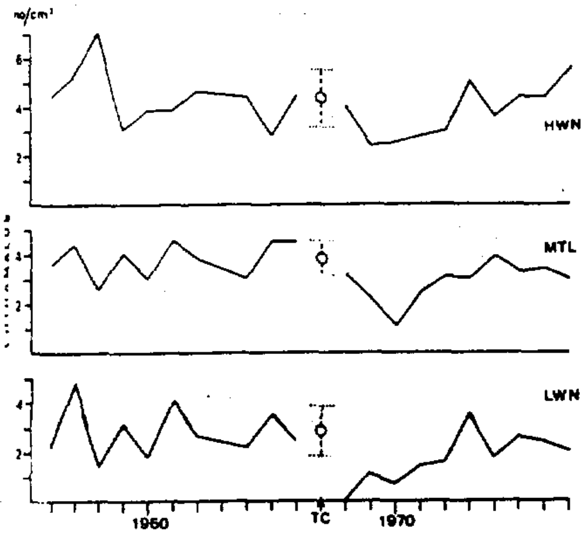


Fig. 15. Fluctuations in the numbers/cm² of *Chthamalus* at MHWN, MTL, and MLWN on the outer edge of the reef at Cape Cornwall from 1956 to 1977. Means and standard deviations are indicated for the 10 yr before the disaster. TC = no counts could be made in 1967, at the time of the spill.

Cape Cornwall (and Sennen Cove)

A greater quantity of oil was stranded at Sennen Cove than at Cape Cornwall, but we have more biological information for the latter. The outer edge of the reef on the northwest side of Cape Cornwall has been surveyed each year since 1956. It is very exposed to wave action and normally carries a population of *P. aspera* as well as *P. vulgata*. In the MHWN to MTL region dense cover by *F. vesiculosus f. linearis* persisted only for a short time (see Table 2) after the disaster, but while present it was very thick. *Fucus spiralis* settled in the HWS region a year later than *F. vesiculosus* in 1968–69, but was never as dense. There was a heavy resettlement by *P. vulgata* and *P. aspera* in the first 3 yr, and this may have helped, together with the wave action, in shortening the period of *Fucus* dominance. As shown in Fig. 15, there was a less severe fall in the barnacle cover at this station than at Porthleven or Trevone. Changes were comparatively slight at the HWN level, where the spaced-out *Fucus* plants allowed some recruitment, and the numbers have been back at their normal level for 5 yr. At MTL the reduction in *Chthamalus* coincided with maximum development of the *Fucus* canopy in 1970, but although all the large algae had gone by 1973 the numbers of *Chthamalus* at this level are still less than those found over the period 1956–66, possibly an effect of the increased *Patella* population. At MLWN the barnacles were smothered by the upward extension of the infralittoral fringe (see below) and *Chthamalus* returned gradually over a period of 5 yr, and is now just within its former range of abundance after a peak in 1973.

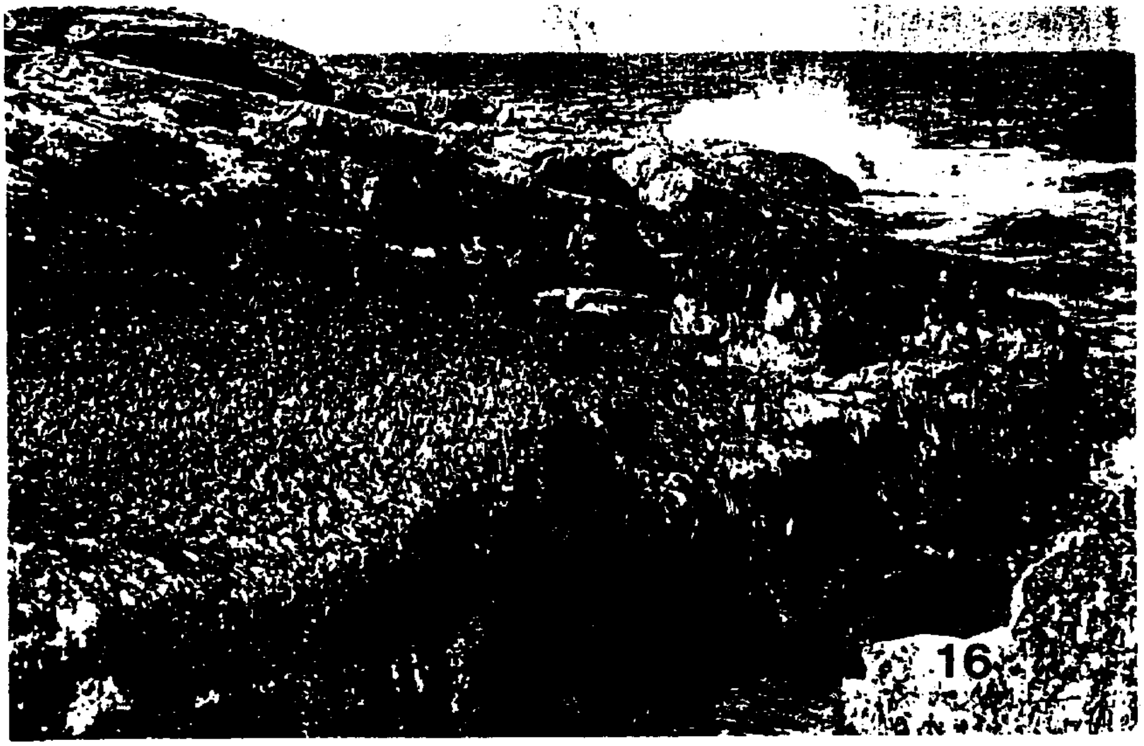
Although *Patella* was wiped out at Cape Cornwall in 1967, *L. nigrolineata* Gray survived. This species is apparently oviparous (Bergerard 1971; Heller 1975) and is usually found at HWS–HWN in association with *Chthamalus*. The survivors showed the effects of the cleaning operations in the same way as the surviving *Nucella* at Porthleven (Bryan 1969) in the form of a growth check on the shell. The numbers increased, and in 1970 and 1971 they could be found aggregated at the base of the clumps of *Fucus*, together with *Patella*, and probably contributed to the eventual removal of the algae. The year 1970 marked the return of other herbivores, *G. umbilicalis* and *L. obtusata*, both in slight shelter, the latter taking advantage of the greater *Fucus* cover than normal to extend over towards the wave-beaten outer edge of the reef. A few young specimens of *Nucella* were found at Cape Cornwall in 1968, and it is assumed that one or two adults survived to breed or else some egg cases survived the cleaning operations as at Porthleven. By 1972 the population of this species had increased considerably, with up to 15/m² on vertical faces on the sheltered side of the reef. The large top-shell *Monodonta* took longer to return here, and was not seen until 1972, when a few *L. rudis* Maton were also recorded.

The inner side of the reef studied at Cape Cornwall, like the rest of Porthledden, of which it is the outer part, retained a full "green flush" into 1968, unlike the wave-beaten outer edge where *Fucus* built up during 1967–68. *Fucus* did not dominate Porthledden until 1969, and it seems possible that the delay may reflect the heavy dispersant treatment received in the inner parts of the bay.

At Sennen Cove there was a similar prolongation of the "greening" and delay in the subsequent development of *Fucus* cover, in an area extending from 100 m west of the pier eastwards to the main sandy beach. The extremely heavy oiling here was treated for a long time with dispersants, and as we know that the oil persisted in the sands for at least a year, it seems possible some components of the dispersant also lingered in the sands and in sand and gravel under the boulders for a shorter period. In this region no molluscs survived to 1968. In 1970 *N. lapillus* and *G. umbilicalis* were occasionally found, and by 1972 all the top-shell species had returned, together with *L. rudis*. Our routine survey station at Sennen is 300 m west of the pier and received less dispersant (Fig. 16, 17). As at Cape Cornwall, *L. nigrolineata* survived when the limpets were killed, and *Fucus* cover developed during the 1st yr, the remaining changes being quite similar to those on the outer edge of the reef at Cape Cornwall (Table 2).

Maen Du Point, Perranuthnoe

We have already mentioned the dispersant treatment applied to Perran Sands at Perranuthnoe, and the effects on the beach infauna have been reported in Smith (1968). The rocks at the northwest end of the beach



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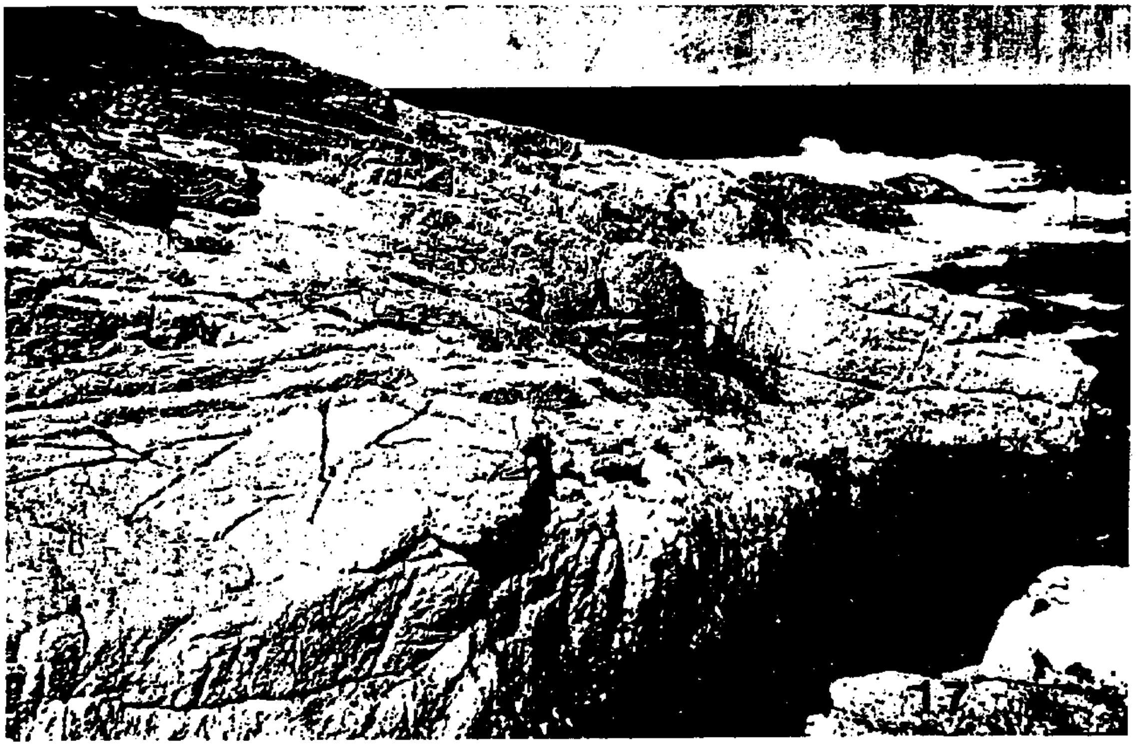

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received moderate oiling, comparable to Godrevy Pt., but up to the beginning of May 1967 many herbivores, including the top-shells, were still alive, though some limpets had died in HW pools close to the thicker patches of oil stranded at extreme high water spring tide level (EHWS).

Oil was still present on these rocks a year later, hence we think that most of the effects then found are due to drift of oil-dispersant patches from the beach operations. This drifting was seen from the cliff top in 1967. At any rate, the observations in 1968 show that most of the limpets had eventually died, though some of the *Monodonta* survived. Much "greening" was then present, together with heavy settlements of *F. vesiculosus*. A slight trace of oil persisted at EHWS to 1970, but by this time it had weathered and was no worse than the more usual small patches of "chronic" oiling that occur afresh every year on most Cornish shores. The maximum cover by *Fucus* varied from 50% (*F. spiralis* at HWS) to 80% (*F. vesiculosus* at MTL–LWN), and by 1970 *P. vulgata* and *P. depressa* had returned in some number. In later years, in spite of the lower mortality that had occurred among the herbivores, and the lesser density of the *Fucus* cover, the changes took as long as on shores treated directly with dispersants (Table 2).

GODREVY POINT

Moderate oiling occurred at Godrevy Pt., but this is National Trust owned land, and lies close to a well-known breeding ground of the Atlantic gray seal. In consequence, direct dispersant treatment was resisted. However, there may have been drift from nearby parts of St. Ives Bay, and the oil itself may have carried traces of the persistent fractions from dispersant spraying at sea a week before stranding. It is thus not possible to be sure, but from circumstantial evidence we believe this is the only station we inspected where the effects can be attributed to the oil. The oil was principally restricted to the inner parts of the reef, from MTL to EHWS, but was nowhere more than 1 to 2 mm thick; it remained in the form of a water-in-oil emulsion for some weeks in spite of exposure to sun and air at low tide. After a month some of the barnacles had managed to clear an opening in the film of oil and showed normal cirral activity when examined in the laboratory. The gut did not contain any traces of oil, in marked contrast to grazing herbivores examined at the same time. The mussels *Mytilus edulis* were apparently unharmed, and we saw no change in the *Nucella* population. Limpets, *P. vulgata*, however, suffered heavily on oiled vertical faces between MTL and MHWS. The limpets must have died, or been weakened sufficiently to lose hold of the rock, or else they moved elsewhere, for their "scars" or homes, where they had lived before the disaster, showed up as light-colored patches against the blackish-brown coating of oil. On flatter surfaces at Godrevy, as on other lightly treated shores, we found limpets browsing on oil-covered rocks, and oil droplets were present in the gut. At this stage of weathering the oil ingested did not appear to be toxic, and a few limpets that had actually grown and increased their shell-size on a diet including oil were found later on another shore.

In spite of the apparent loss of limpets there was no abnormal "greening" of this shore, which often carries patches of *Enteromorpha* and *Porphyra* during the spring. By 1968 some limpets had recolonized the vertical faces affected in 1967 though in lesser numbers than before. Many clear patches of rock could be seen, however, and it was obvious that about 50% of the barnacles had died. Traces of oil remained on flatter surfaces in 1968, but a new settlement of *B. balanoides* took place in the spring, regardless of this remaining oil, and *Chthamalus* also resettled later in the year.

All the oil had gone by 1969, and no obvious long-term effects could then be seen. The mortality at this place was therefore confined to barnacles and limpets that had been thickly coated with oil, and a large section of the shore was apparently unharmed. The whole reef was back to normal after 2 yr, in striking contrast to those shores that were treated with dispersants. The oil did kill some animals, and was thus not as harmless as we thought in 1967 (Smith 1968), but it was obviously much less toxic than many other crude oils and distilled products (Blumer et al. 1970; North et al. 1965; Sanders 1973; Thomas 1973; Kuhnhold 1974; Linden 1976; van Gelder Ottway 1976; Neff et al. 1976; Rice et al. 1976).

SHIFTS IN ZONATION PATTERNS

A most interesting aspect of the process of recolonization of the denuded shores was a change in zonation patterns resulting from alterations in species interactions and the differing time scales of resettlement.

Such a change was most obvious on the outer edge of the reef at Cape Cornwall (Fig. 18), where there was an especially luxuriant regrowth of algae by the spring of 1968. On the traverse investigated, the infralittoral

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FIGURES 16 AND 17. Sennen Cove, wave-beaten rocks at the south end.

FIG. 16. May 21, 1970. Near the camera there is dense cover by *F. spiralis* (*upper edge*) and *F. vesiculosus* f. *linearis*, but farther to seaward the algal cover is already thinning out as the new population of herbivores develops. Fig. 17. June 1, 1977. A more or less complete return to normal *Patella/Chthamalus* dominance has occurred. There are a few tufts of *F. vesiculosus* in the barnacle zone (as immediate foreground), and the black lichen *Lichina pygmaea* has recovered its former abundance at high-water (*upper left side*).

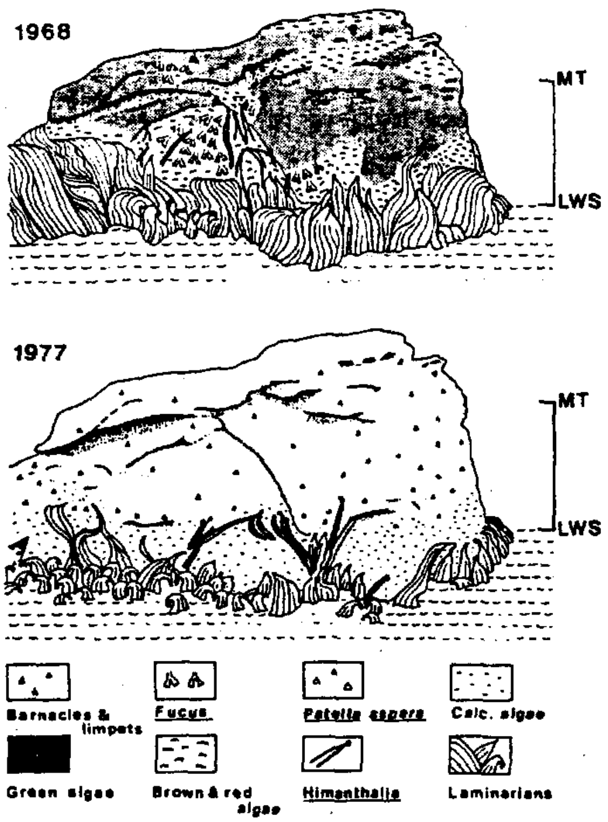

FIG. 18. Cape Cornwall, wave-beaten outer rocks: sketches based on photographs showing the change in zonation after the disaster. *Upper*, situation in May 1968, 13 mo after all herbivores had been killed by dispersants; below, situation 9 yr later in May 1977, after restoration of the herbivore population. Upper limits of *Laminaria digitata* and *Himanthalia elongata* were 1.5 to 2 m higher in spring 1968 than in spring 1977. MT = mean tide level, LWS = mean low water spring tide level.

fringe (principally *L. digitata*, though *Alaria esculenta* and *L. hyperborea* are present), was raised above its normal upper limit by 1.5–2 m, so that quite large plants of *L. digitata* were growing at between MLWN and MTL in places where there was previously a community of barnacles, limpets, and smaller algae. A corresponding upward shift had taken place in *Himanthalia elongata*, which at this place normally forms a belt overlapping the infralittoral fringe and the lower third of the midlittoral. Plants with well-developed "thongs" were present up to MTL, and "buttons" occurred right up to MHWN. In addition *Corallina* was much better developed and bushier than usual. There was dense cover by young plants of *F. vesiculosus* f. *linearis* from MHWN to MTL, and some patches of this extended right down to MLWN, mixed with the *Himanthalia* and *Laminaria*. After 3 yr the *Laminaria* had retreated, but *Himanthalia* was still present in a thick belt at least 1 m above its usual level, and a return to normal patterns was not seen until 1973–74, after the peak in the limpet population had been reached.

This upward shift in the algal zonation must be related to the absence of grazing pressure by limpets. On such a wave-washed site it would appear that this biological interaction may be more important than a physical factor such as desiccation, which has usually been accepted as the cause of the upper limit of the infralittoral fringe. This hypothesis probably still applies to sheltered shores where *P. aspera* is absent and limpets less common. At wave-beaten edges of the reef at Cape Cornwall *P. aspera* is normally dominant in the region showing the change in zonation, and occurs in smaller numbers right up to MHWN. This species recolonized between MLWN and MTL in small numbers in 1967–68, and had reached a length of 9 to 17 mm by the spring of 1969. These measurements indicate a slower rate of growth than in *P. vulgata* and probably a slower build-up in the population, hence the restoration of the normal algal zonation at this level must be attributed also to the larger number of *P. vulgata* present at MTL and their subsequent movement down the rock. *P. aspera* increased later, and the species persisted in smaller numbers at MTL to MHWN for five years after the end of the *Fucus* canopy.

Other changes in zonation have occurred, less obvious than the shift in algae, but involving similar vertical distances. Most of them were upward extensions of species which took advantage of the shelter and increased moisture provided by the *Fucus* cover. Thus, in 1969 on several shores, including Lizard Pt., Porthleven, Perranuthnoe, Sennen Cove and Trevone, *S. rupestris* became abundant at MTL under the canopy of *F. vesiculosus* and *F. serratus*. In such places it was replacing the normal barnacle zone (cf. Moore 1934), and was frequently found in association with other organisms more usually found towards low tide level or in pools, including encrusting coralline algae ('lithothamnia'), the barnacles *B. crenatus* and *B. perforatus* and the LW limpet *P. aspera*. *Spirorbis rupestris* was not confined to "lithothamnia" coated surfaces, and also occurred on the bare rock and on limpet shells. The uplift of *B. perforatus* was particularly noticeable at Porthleven and on the outer edge of the reefs at Trevone. Some specimens occurred up to MHWN where they survived for a year or two after the end of the *Fucus* cover.

During the period of *Fucus* decline, especially after 1972, it was quite easy to distinguish places where the algae had been abundant by the presence of the gradually dying remains of all of these uplifted animal zones, and by patches of "lithothamnia." The general abundance of the crustose coralline algae was noted on all *Torrey Canyon* shores, but some of the growth of these species could be related to the initial absence of limpets as well as to the greater moisture levels under the *Fucus*. Existing limpet "fronts" show clearly the heavy grazing pressure also exerted on such calcareous algae.

It would seem therefore that the disturbance of the ecosystem caused by removal of all grazing animals had two effects on zonation; one was related to a lessening of desiccation caused by algal growths; the other was more complex, and resulted from direct interaction between the herbivores and the plants. It seems possible that corresponding changes have occurred elsewhere through oil pollution, even when dispersants have not been used (cf. Thomas 1975).

LOSS OF SPECIES

The absence of evidence showing loss of a species has often been claimed to show that the dispersants had no long-term effects on the ecosystem (e.g. Shelton 1971; Wardley Smith 1976). We have no data for the algae, which are still in need of a complete survey. However, one animal species has not returned to shores directly treated with dispersants: the rare, warmwater, hermit crab, *Clibanarius erythropus* (Southward and Southward 1977).

The British population of *Clibanarius* appears to be a precarious one, maintained by occasional settlements of planktonic larvae derived from the more abundant populations in south Brittany, and it is possible that recent climatic and hydrographic changes may have reduced the chances of recruitment.

There is a surviving colony of this species at Wembury, South Devon, outside the affected area, and a few specimens escaped at Great Hogus rock, Marazion, when others were killed on the causeway rocks. But at Lizard Point, Porthleven, and Trevone the species was wiped out and has not returned; the latter locality was the only known record on the north coast of Cornwall.

Strictly speaking this species has not been totally lost from the Cornish fauna, but the known population in Britain has been reduced by half from that existing before the *Torrey Canyon* disaster. We could regard this as the LC$_{50}$ for the species.

Discussion

The widespread mortalities on west Cornish seashores resulting from the *Torrey Canyon* clean up provided a large-scale experiment on the successional sequence of rocky shores and on the influence of herbivores and predators on the ecosystem. The small amount of prespill data, the lack of sites where oil was left entirely untreated, and uncertainties of how much dispersant reached marginal areas have prevented accurate statistical comparisons. However, the frequent long stretches of coastline showing dispersant damage has meant that the first few years of recolonization relied more on larval dispersal than on local adult migration, a factor that has always interfered with small-scale experiments on rocky shores (cf. Southward 1956; Aitken 1962; Emson and Faller-Fritsch 1976). Incomplete as the results are, we still have a mass of information which helps to illuminate current theories on the structure and stability of ecosystems.

Reference to almost any recent ecological journal or book will show the continuing lack of agreement on what constitutes stability, and how it is related to diversity (Odum 1971, 1975; Orians 1975; May 1975; Menge and Sutherland 1976; McNaughton 1977). On rocky shores environmental stress by physical factors can be important (Sanders 1968; Lewis and Bowman 1975; Bowman and Lewis 1977) but biological interactions appear to provide many of the reasons for the community patterns observed (e.g. Connell 1972, 1975). In a simple system with high environmental stress (Menge 1976) interspecific competition for space is important in wave-exposed areas, predation important in shelter. In more complex communities both predation and competition for space and food operate in different facets of the community or at different tidal levels (e.g. Connell 1970; Luckens 1975; Branch 1976; Menge and Sutherland 1976). However, experimental removal of a dominant predator or grazer results in an increase in biomass, and often reduces species diversity (Paine 1966, 1971; Paine and Vadas 1969; cf. Connell and Orias 1964; McNaughton 1977).

It should thus be no surprise that a disturbance on the scale of the *Torrey Canyon* affair can cause long-term instabilities to a typical northeast Atlantic rocky shore community, and shorter-term changes in zonation patterns. It was at one time thought that the typical shore of the region was dominated by belts of the large brown seaweeds, and that the transition to a barnacle- or mussel-covered shore in exposed points was a direct effect of the wave on settlement and survival of the plants, and there was some experimental evidence to support this view (Hatton 1938). However, experiments carried out since 1946 show that the negative correlation between wave action and a *Fucus*-dominated community is indirect, mediated through the grazing activities of herbivores, mainly limpets (Jones 1948; Lodge 1948; Burrows and Lodge 1950; Southward 1956; Aitken 1962). Removal of the limpets from a west coast shore of Britain produces a regular succession: (1) a film of benthic diatoms and other unicellular and filamentous algae, a brief transitional phase that may be obvious only in late autumn and winter when lack of light reduces algal growth; (2) a green flush of *Enteromorpha*, which may dominate for a year; (3) heavy settlement of *Fucus* in the 1st–3rd yr, replacing the *Enteromorpha*; (4) settlement and growth of *Patella* follows, so that further increases in *Fucus* are prevented by grazing during and after the 3rd yr; (5) the older plants then die off or are removed by *Patella* grazing; (6) the rock is available for resettlement by barnacles in the 5th and 6th yr, and the number of limpets falls as their food supply is reduced; (7) by the 6th and 7th yr or so there is a return to a *Patella*–barnacle dominated community, and the cycle could be restarted again. At the end of the field experiments quoted above, the cleared areas could be distinguished from the surrounding natural communities by a total absence of large algae above MTL.

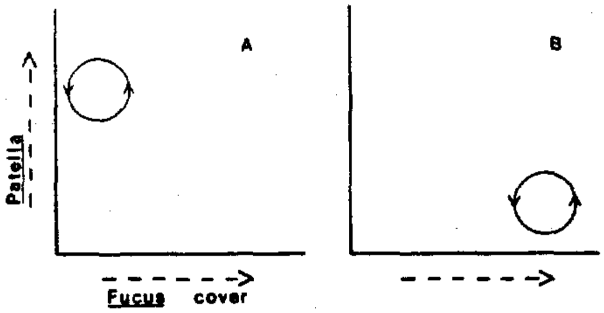

FIG. 19. Model of the theoretical relationship (Lotka-Volterra plot) between the numbers of a herbivore (*Patella*) and the density of an alga (*Fucus*). A, On wave-beaten shores; B, on sheltered shores.

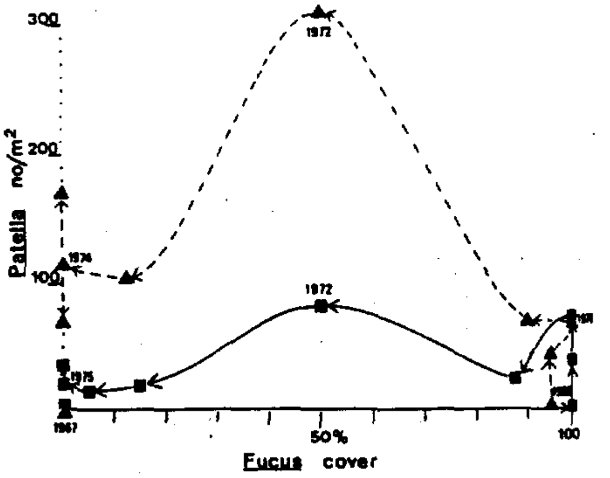

FIG. 20. Number/m² of *Patella* plotted against the percentage cover of *Fucus* at MTL Trevone (solid line and squares) and at MTL Porthleven (broken line and triangles) to compare with Fig. 9. Dates of some of the points in the sequence are shown.

Natural cycles with the same succession occur on small scale, due to storms, beach movements, or similar factors causing local reduction in the limpet population, and may follow shipwreck or harbor construction where new surfaces are exposed to the sea (Seshappa 1956; Southward 1956; Moore 1939). Not all of the steps in this succession necessarily follow the preceding stage, in agreement with Connell (1972). Barnacles can settle immediately on cleared surfaces at some seasons (personal observations), and limpets can follow *Enteromorpha* without a *Fucus* phase, but most often the full sequence is seen. The same cycle of events was followed on the shores badly affected by the *Torrey Canyon* clean up, but the situation was complicated by the fact that all herbivores and some of the barnacles were killed. In the absence of *Patella* the littorinids can exercise control over algal regrowth (cf. Menge 1976; Keser et al. 1977), while dead barnacle shells would be expected to provide a surface favourable to settlement of spores (cf. Menge 1976). Nevertheless, the main course of recolonization has been similar, and, as on the experimental areas, there have been fluctuations in zonation patterns and the sequence has ended with a shore devoid of large seaweeds (Burrows and Lodge 1950; Southward 1956). Only the time scale has been different. Along the wave-beaten edges to the reefs and in a few spots where *Fucus* failed to become dominant the cycle was completed in 5–7 yr; elsewhere periods of up to 10 yr have been noted. This longer period to regain equilibrium may be due to (1) residual toxicity, with delays up to 1 yr, (2) the sheer scale of the mortality restricting possible migration of adult herbivores such as was possible on small experimental areas and must happen naturally, (3) the removal of all herbivores, as noted above. If a future major spill of toxic oil should occur, more attention must be paid to these aspects of recolonization, by sampling for oil and dispersant residues, and by examining the edges of the treated areas for migration.

In the absence of large-scale disturbances and where environmental fluctuations are of small amplitude, the balance between the large seaweeds and the herbivores either becomes stabilized at some particular point in the cycle, or undergoes cyclic changes of smaller radius (Fig. 19). Increasing wave action favors the limpets and barnacles while increasing shelter and increasing shade favor the algae, but in a natural system the two extremes — all algae, or all barnacles and limpets — are rarely found. Instead there is usually a mosaic related to small-scale local variations in wave action, insolation, desiccation, herbivore density, and irregular predation by the next trophic level (*Nucella*, crabs, fish, and birds). We are here considering a very simplified version of the system, and have not taken into account other common animals such as mussels (Lewis 1972, 1976), the pseudoperennial algae such as *Laurencia* and *Corallina*, and the smaller and encrusting algae which are also grazed by the herbivores. Even with these additional factors, the situation is still simpler than in other parts of the world where limpets are more specialized, and more species exist in closer relationship with their food organisms (Branch 1976).

We can consider the fluctuations in algae, herbivores, other sedentary animals and predators resulting from the *Torrey Canyon* affair as a series of damped oscillations in which the delay in response of one organism to changes in the other is much greater than in a typical Lotka-Volterra system (cf. Odum 1971). The time scale of the oscillations is prolonged since breeding and recruitment are annual (or less frequent) and the typical organisms can live for a long time: *Fucus* 4–5 yr (Knight and Parke 1950), *Patella* 20 yr (Fischer-Piette 1941), *Chthamalus* 5 yr. The point at which the limpet-*Fucus* balance reaches equilibrium can still be illustrated in terms of Lotka-Volterra equations, though this is a great oversimplication (cf. Harte and Levy 1975). By plotting the changes on *Torrey Canyon* affected

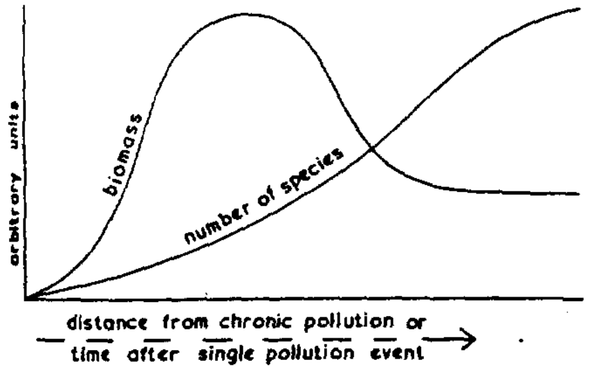

Fig. 21. Theoretical representation of the effects of disturbance to the ecosystem on rocky shores. The ordinate scale can indicate distance from a source of chronic pollution, or (as in the *Torrey Canyon* sequence) the time from a single catastrophe.

shores compared with the model (Figs. 19–20) we can see that the relationship swung first to a part-cycle representing the more sheltered shore type of community, then to a part-cycle typical of more exposed shores, but eventually the system runs off the graph since the food supply is drastically reduced. The relationship between *Patella* and *Fucus* is thus confirmed to be much less of a specialized "prey"–"predator" system than that found between the kelp *Egregia* and the limpet *Acmaea insessa* (Black 1976) and some of the South African species (Branch 1976). *Patella* can and does graze on many other food organisms, and is also capable of modifying its grazing pressure by extensive migration (Aitken 1962) where local variations exist.

In theory the balance of the intertidal rocky shore community could be disturbed (cf. Cowell 1976) by any man-made event that alters the abundance of one of the common species. It is most often the herbivores that are sensitive, whether to oil, dispersants, sewage, or other toxins, and hence the effects are usually seen as a transition, temporary or permanent, towards the sheltered shore type of community (Baker 1976a). Such a shift in the equilibrium reduces the number of species, though the total standing crop (biomass) may be higher. We may express the relationship as a general principle (Fig. 21). based on the model suggested for polluted rivers (e.g. Hynes 1950). Apologists for pollution, and some fishery technologists, like to think of the lower diversity mode of such a system as an increase in productivity (cf. Regier and Cowell 1972; Cowell 1976). In the intertidal habitat we must be careful to separate increases in biomass, as in the growth of perennial seaweeds. from the lesser annual primary production.

A final point to be considered in relation to the time scale of recovery is climate. This is one of the factors that may have helped to mitigate some of the effects of the *Torrey Canyon* on marine life in Cornwall. though it may have contributed to the mortality of certain species (cf. Crapp 1971a). Cornwall is close to a boundary between zoogeographical regions. It is at the southern limit for many boreal species, but temperatures are high enough to permit some warm-temperate species to live and reproduce. In colder waters we would expect the oil to weather much more slowly and there would be slower recolonization by the organisms affected (Prouse and Gordon 1976; Vandermeulen et al. 1977). On the other hand, in low latitudes blackening by persistent oil can lead to very high temperatures in the intertidal zone due to absorption of solar radiation (Chan 1977a; cf. also Straughan 1976) and this could delay recolonization even though the progress of weathering would be faster and the period of settlement greater in the tropics (cf. Stirling 1977). On Cornish shores the oil weathered quite rapidly when it was given the chance, and resettlement was not noticeably influenced, giving us the best of the two extremes. However, the position at the edge of distribution of certain species has contributed to the partial loss of a rare animal and may have been one of the causes of the delay in recruitment of southern species such as *P. depressa* and *Monodonta lineata*.

Conclusions

It is unfortunate, to say the least, that the myth of rapid and complete recovery of *Torrey Canyon* affected shores has become enshrined in the literature, and has even reached elementary textbooks on pollution ecology (e.g. Mellanby 1972). We must emphasize again, therefore, that recovery has not been rapid. Recolonization, first by algae and then by animals has taken place slowly year by year, the number of returning species increasing as dominance by opportunists and early colonizers became reduced. Many of the species breed for a short time only once a year, and not all of the animals have planktonic larvae. Return to normal has therefore been very protracted. As might have been expected, the lightly oiled wave-beaten rocks that received moderate dispersant treatment have shown the most complete return to normal, taking about 5–8 yr. Other places that received the brunt of dispersant treatment have taken longer, from 9 to 10 yr, and it is the opinion of other ecologists besides ourselves that some shores are still not normal. This is a partly subjective estimate, based not only on species richness but on the presence of a wide range of sizes and age-groups of the longer lived species and on the "photographable" quality of the mosaic of contrasting organisms that characterizes a mature and balanced intertidal community on the open coast of Cornwall.

The effects have been more obvious, and have probably been detectable for longer periods on the west coast of Britain than they might have been in places where limpets are less abundant or in regions where the genus *Patella* is absent (cf. Stephenson and Stephenson 1972). However, in some regions where limpets are less dominant there is a more complex pyramid of herbivores and several levels of predation (e.g. Pacific North America; Connell 1970; Menge and Sutherland 1976), and the aftereffects of oil spills can be of still greater severity (North et al. 1965; North 1973; but contrast Chan 1977b). It is perhaps the one tangible benefit of the *Torrey Canyon* affair that it drew universal attention to the dangers of dispersant. Thus our misfortune in Cornwall has helped prevent excessive use of dispersants to clean up later spills such as the Santa Barbara blowout and the *Arrow* wrecking (Straughan 1971; Canada, Ministry of Transport 1970), and has eventually lead to some changes in U.K. official policy with regard to treatment of spills.

In discussing the use of dispersants to clean the shores affected by the *Torrey Canyon*, the editor of the Marine Biological Association report (Smith 1968) says (p. 178) "the decision to use detergent for the dispersal of the oil was taken on the view — with which there will be general agreement — that the preservation of the coastal amenities was of first priority, and in the hope that the effects of the detergents on marine life would not be catastrophic." This view has been applauded and amplified beyond the original in a review by Mackin (1973). The suggestion that there was no alternative approach to the problem than widespread dispersant application is not borne out by experience in Guernsey and France and by later spills. It is quite clear now, with hindsight, that the developers of the dispersant technique never thought it would be used on a massive scale. Thus, Wardley Smith (1962) believed that only large local authorities, with considerable tourist interests, would be able to afford the cost of cleaning up their beaches, and urged more measures to prevent spills. But in Cornwall, in 1967, cleaning operations soon got out of control, with dispersants issued in virtually unlimited quantities and the armed forces called in for assistance. In Guernsey there was no help from the military, and as dispersant was fully costed only a small quantity was used; the effects on marine life were minimal, but the tourist interests were unharmed. In Brittany use of dispersants was also restricted, though more oil was stranded there than in Cornwall, yet tourist interests were again unharmed.

Much depends on ones view of what constitutes recreational amenities. The House of Commons Select Committee on Science and Technology (Great Britain, House of Commons, 1968) took the view that "to many people one of the particular delights of visiting the seaside is to study and enjoy the vast variety of the fauna and flora." Cowell et al. (1972) endorse this and note "shores that were cleaned in order to render them suitable for holiday makers are now very difficult to travel over and will remain so for several years." That is, a layer of oil that might have degraded within a year was exchanged for slippery thickets of one or two species of seaweed of much greater persistence. It is obviously more important to consider amenity use when oil is stranded on sandy shores close to tourist centers, but even then, during the *Torrey Canyon* operations dispersants were used in such large quantities that some of the oil was driven deep down into the sands and only released later during winter storms. Similar consequences of dispersant application to sandy beaches are still being reported after recent oil spills, such as the *Jakob Maersk* in Portugal (Duerden 1976) and the *St. Peter* in Colombia (Hayes 1977; D. J. Crisp personal communication), showing how little seems to be learned at the practical level. It is only now, 10 yr later, after studying the results of other strandings and of laboratory experiments that one can see how fortunate we were in Britain that the *Torrey Canyon* disaster was no worse. If the wreck had happened on a more embayed section of the coast or in an estuary complex, if the tanker had been carrying distilled products or one of the more toxic crude oils, if all the oil had come ashore and had been treated with an equivalent ratio of dispersants, in these cases we might indeed have been closer to ecodisaster.

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OIL POLLUTION CONTROL, A COOPERATIVE EFFORT

A STUDY OF THE EFFECTS OF THE SAN FRANCISCO OIL SPILL ON MARINE LIFE PART II: RECRUITMENT

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ABSTRACT

A study of marine organisms on intertidal transects encompassed the central theme of observing the effects of the San Francisco Bunker C oil spill of January 18, 1971. From a comparison of pre-oil and post-oil transect data with computation of 95% confidence intervals for population means, it was estimated that 4.2 to 7.5 million marine intertebrates, chiefly barnacles, were smothered by the oil. In subsequent observations from 1972 to 1974, the sample counts of invertebrates had returned to, and in some cases surpassed, pre-oil transect levels. No lingering effects of the oil spill have been noted in any of the marine species.

INTRODUCTION

On January 18, 1971, during the early morning hours, two Standard Oil tankers collided under the Golden Gate Bridge in thick fog, spilling 840,000 gallons of Bunker C oil into the coastal waters of the San Francisco Bay area of California (figure 1). During the following days, tidal currents carried the oil to nearby reefs in Marin County where my students and I had established various marine life transects, some as early as 1958. Comparisons of the pre-oil and post-oil counts on these transects constituted the analysis of the damage to marine life by this spill. The results of studies conducted through August 1971 were published in the report, *A Study of the Effects of the San Francisco Oil Spill on Marine Organisms, Part I* [2]. The study on recruitment includes data gathered through April 1974.

Sampling Methods and Procedures

There were 37 transects involved in the study. The transects, usually 10 meters long, were chosen from random numbers. A square-meter quadrat frame, with at least ten square-decimeter sections within the frame, was moved along a ten-meter line, and organisms inside the frame were counted.

The amount of residual oil on each transect was also recorded, rated according to the percentage of square meters with oil:

N = no square meters had oil
\+ = 1-25% with oil
++ = 26-50% with oil
+++ = 51-75% with oil
++++ = 76-100% with oil

The statistical 95% confidence interval based on sample data was used consistently to determine the interval within which we may expect the population mean or population proportion. If, on the basis of repeated sampling, 95% confidence intervals for the population mean are set up, then approximately 95% of these confidence intervals will actually contain the true population mean [6]. The hypothesis of significant difference between population means was tested by statistical analysis, comparing data of different sampling dates and transects: $H_0: \mu_1 = \mu_2$; $H_1: \mu_1 \neq \mu_2$; $\alpha = .05$. Reject H_0 if test statistic Z is > 1.96 or < -1.96.

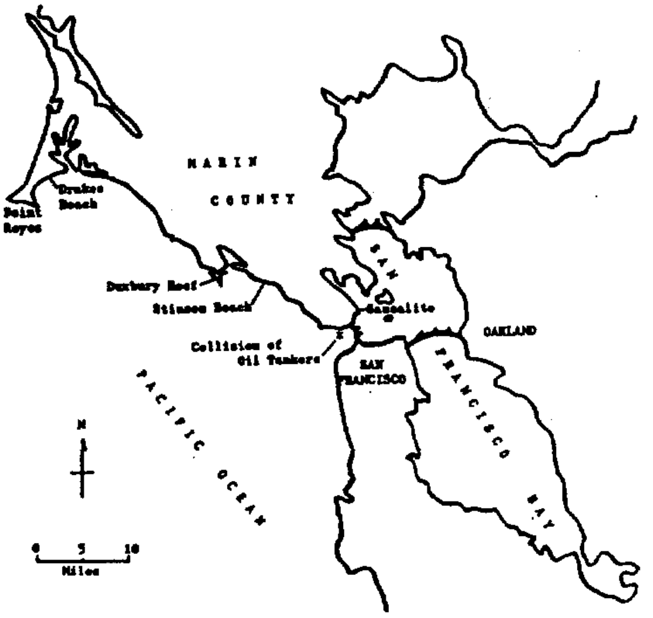

Figure 1. Localities of the 1971 San Francisco oil spill

Observations and Findings up to 1974

Sausalito Data

In the early days of the spill, the Seal Rock area was blanketed with oil. The transect here had a plus 4 (++++) rating with all of the square meters heavily covered with oil. Based on the 95% confidence interval, an estimated range of 3.6 to 6.2 million barnacles (33.6 to 35.5% of the population), *Balanus glandula* and *Chthamalus dalli*, may have died in this transect study area of 1,000 square meters in the general Bridgeway section of Sausalito.

This same transect in May 1972 showed solid recruitment of marine life to the study area. Figure 2 shows that these acorn barnacles have nearly tripled in the sample counts from a mean of 93 live/dm^2 in May 1971 to 278 live/dm^2 in May 1972.

By May 1972 the oil had eroded off to a plus 2 (++) residual oil rating, leaving bare spots and many barnacle scars. Small acorn barnacles, about 1 mm in size, were seen scattered in profuse numbers; much of the new barnacle recruitment has settled on the old barnacle base scars.

The data from this random sampling indicate that the planktonic barnacle larval population in San Francisco Bay appears to be following a sound recruitment pattern, such that the 1972 live population mean is significantly different from that of 1971 by an interval estimate of difference ranging from 191.1 to 268.5 per dm^2. At Fort Baker, a no-oil transect was established in July 1971 as a control reference of comparison with the Seal Rock oil transect. There was no significant difference between the live population means of the acorn barnacles of these two transects in 1971. A year later, in 1972, there also was no significant difference between the live population means, indicating that the recruitment for the oil transect was on a comparable level with that of the no-oil transect.

The limpet sample count for *Collisella* spp. (formerly *Acmaea* spp.) increased from a total of 21 in 1971 for 63 random dm^2 to 90 in 1972 for 60 dm^2. The movement of these flat gastropods is quite variable, so the higher density count cannot be automatically construed as a recruitment growth pattern.

The most mobile of the Sausalito intertidal invertebrates are the shore crabs, *Pachygrapsus crassipes* and *Hemigrapsus nudus*. Although the oil spill killed off many crabs [2], the surviving crustaceans were able to dodge into the crevices and maintain a fairly consistent population level through 1972 (figure 3).

Stinson Beach Data

This long sandy beach was covered with oil during the early days of the spill. Standard Oil Company reported that its mechanical graders and lifters, in the process of removing the oil and debris, had disrupted and removed, on the average, the upper six inches of the sand's surfaces. Since this upper portion of sand contained a large percentage of the transect population, it was not possible to estimate the number of dead organisms. In Part I of this report on the spill [2], I could not relate the drastically reduced marine life density at this transect as a direct result of the oil spill. Three major species have been observed at the Boyle's sand fence transect near Calle Del Sierra: *Emerita analoga*, the mole or sand crab; *Nepthys californiensis*, the sand worm; and *Orchestoidea californiana*, the beach hopper. The same species were also counted at Drakes Beach where no oil had been reported. A comparison of the combined mean number per square meter for all three species since 1965 shows a downward trend in figure 4.

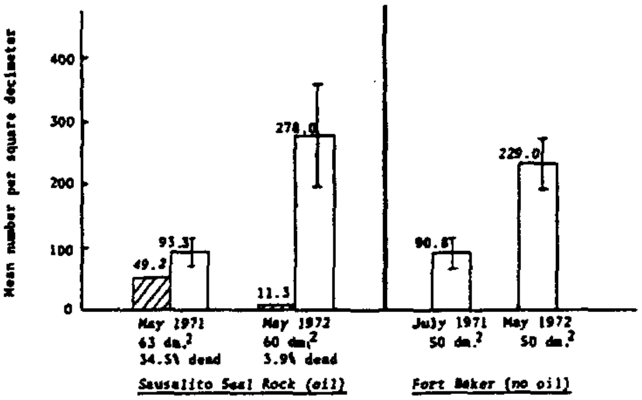

Figure 2. Comparison of barnacles, *Balanus glandula* and *Chthamalus dalli*, for transects in Sausalito (oil) and Ft. Baker (no oil)

▨ dead ☐ live I 95% confidence interval for population mean

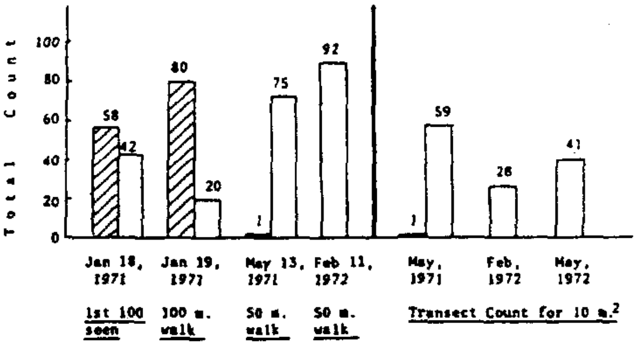

Figure 3. *Pachygrapsus crassipes* and *Hemigrapsus nudus* counts at *Sausalito Seal Rock reef area*

▨ dead ☐ live

Prior to the spill, the marine polychaete, *Nepthys californiensis*, was quite abundant in the Stinson Beach transect, but since the spill, this worm has not returned in post-oil counts. On the other hand, the worm has continued to be present at Drakes Beach, the control transect. Both areas currently show low densities of marine organisms. Although the oil may have had its smothering effect, perhaps the major contributing reason for the poor recruitment can be related to an ecological sand disturbance of winter and summer conditions rather than the spill and cleanup disruptions.

Guard and Cobet [3], from their experiment with Bunker fuel oil on beach sand, reported that normal beach conditions quickly returned as a result of effective cleanup combined with the natural processes of evaporation, dissolution, and beach erosion. The sands of Stinson Beach today do not show much effect of the 1971 oil spill.

Duxbury Reef Data

The major locality for the oil spill study was this large 66-acre shale reef in Bolinas, California, about twenty miles north of San Francisco. Quadrat studies have been conducted here since 1958. A total of 33 transects were used for statistical comparison; 26 of these were established before the spill. Data for the most heavily affected areas revealed 20% of all organisms counted were dead. An estimate of over one million organisms had been suffocated by the oil, with the barnacles and limpets suffering the highest mortality in relation to their population densities, 34% and 22% respectively for the samples studied.

By the summer of 1971, the oil was fast disappearing from the reef's rocky surfaces, chipped off by water erosion. The present condition of the reef appears to be quite healthy. About 95% of the oil has eroded away and recruitment of marine life is generally good, with a few exceptions. The reef's status as a state marine reserve since 1971 has generally protected the marine invertebrates from collectors. A chronology of the effects of oil on the marine organisms follows.

1. **Marine Plants.** Although the surf grass, *Phyllospadix scouleri*, and other upper-zoned algae, *Gigartina* spp. and *Endocladia muricata*, suffered some die-offs at the tips of the plants from the oil, their growth is now as luxurious as ever.

All the marine algae seem to be growing at pre-oil densities. The macroscopic crustose, *Ralfsia pacifica*, has been growing profusely on all rocky surfaces, including on top of old oil, from the low to the high tide levels. There had been thick growths of the green algae, *Urospora penicilliformis*, particularly on mussels which had oil on their shells. This filamentous algae, which is common on upper intertidal boulders [5], continued to be present throughout the summer of 1972, but at only 25% of the density observed during the post-oil summer months of 1971. There were small traces of this algae during the summer of 1973. No harmful effect on marine fauna was attributed to this algae growth of *U. penicilliformis*.

2. Snails. The black turban snail, *Tegula funebralis*, is a dominant species, occurring in large numbers throughout the Duxbury Reef shale flats. In our 11-transect sample of 100 square meters, this snail had a fluctuating sample mean number between 15 and 40 per square meter (see figure 5).

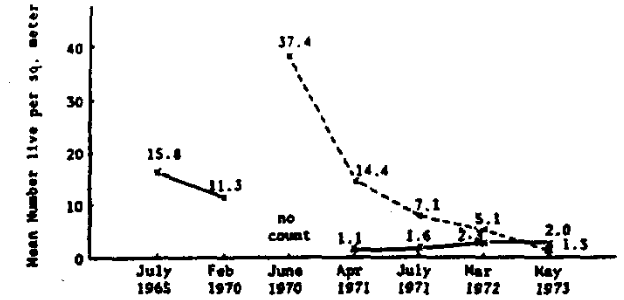

Figure 4. Comparison of transects at Stinson Beach and Drakes Beach for three species combined: *Emerita analoga, Nepthys californiensis,* and *Orchestoidea californiana*

—— Stinson Beach Transect (100% oil, graded)

- - - Drakes Beach Transect (non-oil)

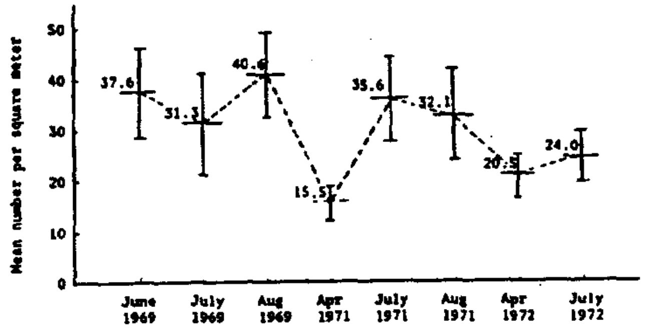

Figure 5. Summary of *Tegula funebralis*, Duxbury Reef, 11 transects

+ sample mean

I 95% confidence interval for population mean

With nearly all the oil eroded from the expansive shale reef, *T. funebralis* is grazing in large numbers, and present densities appear to be comparable to pre-oil status except for April of 1971 and 1972 which had shown significant lows. Further monitoring will determine if these are cyclical lows for this species. The April 1971 decrease, however, is probably partially associated with the spill.

The small periwinkle snail, *Littorina scutulata*, is in a very healthy state of recruitment. Some of the square meters in the berm transects contain thousands of these snails. They were the first marine organisms observed crawling on top of encrusted oil as early as three months after the initial deposit of oil on the reef.

The only snail which appears to be on the verge of extinction is a very small population of *Littorina planaxis*, found in a small section of the Area A berm. Although it is very common on other reefs throughout central California, this grey periwinkle snail has never been abundant in our counts; pre-oil counts yielded total transect numbers ranging from 18 to 24, while counts in 1971 to 1973 ranged from 0 to 7. The 1971 oil spill was a major factor in reducing the total counts, with only two observed in a recent April 1974 count.

3. Mussels. This reef is blessed with a large population of approximately 1,200,000 mussels, *Mytilus californianus*. The mussel beds form a large chenille-like rug on top of this reef, covering about 2,000 square meters. Since about 50% of the beds had been covered with oil, a high rate of mortality was expected; however, mussels in the Area C transect beds, covering about 1,000 square meters, survived the oil with only a 2% loss, or 12,000 dead. The high survival rate, despite the blanket of Bunker C oil, is probably due to their effectiveness in keeping their shells closed during the time of oil coverage. Kanter, in his study of the effects of crude oil on *M. californianus* [4], also found that this avoidance behavior was very significant for survival. The present condition of mussels indicates a healthy state of recruitment; many mussels measure 2 to 5 cm, a sign of new population growths. Statistical analysis of data for July 1971 through December 1973 showed significant differences in population mean when compared to pre-oil data through June 1971 as shown in figure 6.

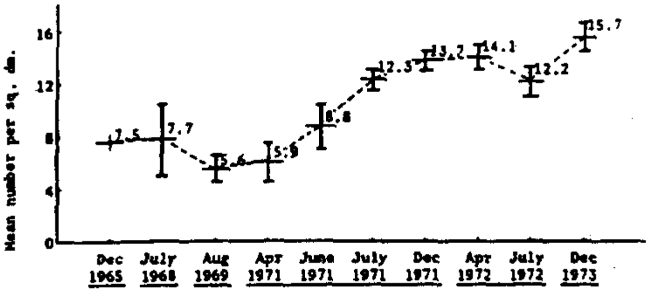

Figure 6. Live *Mytilus californianus* for Duxbury Reef, Area C transect, 100 square decimeter sampling

+ sample mean

I 95% confidence interval for population mean

Like Kanter [4], I also have concluded that the survival of the sea-mussel, *M. californianus*, is probably due to a combination of factors: intraspecies variations, size, age, geographical location, tolerances to natural oil seeps, seasonal influences, and tidal-current conditions at the time of oil contamination.

4. Limpets. Several species of limpets, *Collisella* spp., together form a solid picture of density recruitment on the Duxbury Reef berm area. Figure 7 presents data dating back to 1964.

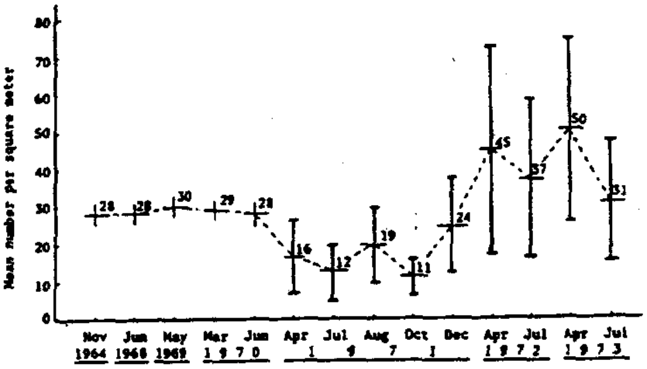

Figure 7. Live *Collisella* spp. for Duxbury Reef Berm A-8, 9; 20 square meters

+ sample mean

I 95% confidence interval for population mean

The pre-oil sample means were very consistent, from $28/m^2$ to $30/m^2$, while the sample means during the immediate year following the oil spill varied from $11/m^2$ to $24/m^2$. The years 1972 and 1973 showed a large influx of limpets to the transect sites. Many of these limpets were less than 1 cm in length indicating young populations, an encouraging ecological sign of recruitment. Conversely, there has been a steady decrease in dead limpets, which are still "glued" to the shale rock by the old oil and straw matrix. For berm transects totaling 30 square meters, dead limpets have decreased from a mean of $9.3/m^2$ in April 1971 to $0.9/m^2$ in April 1973.

5. Barnacles. My initial report stated that some one million barnacles were smothered by oil; however, the subsequent natural recruitment of barnacles, *Balanus glandula* and *Chthamalus dalli*, to transect sites has been successful. Where the oil once covered the shale berm, for instance, thousands of small barnacles, mostly less than 2 mm in diameter, now occupy the bare rock surfaces. The sample mean for three berm transects, 30 square meters, has increased from 13.5/m^2 in 1971 to 50.1/m^2 in 1972 to 81.8/m^2 in 1973. Each successive year since the spill has shown a significant difference between the live population means for these transects.

Figure 8 affords two notable observations in the comparison of two transects with no residual oil to seven transects with 76-100% oil coverage, including the berm and mussel bed transects. The oil transects, with higher ratio of dead to live due to oil, showed an almost threefold increase, a recruitment comparable to that of the no-oil transects and similar to that of Sausalito and Fort Baker. Where wave actions were more vigorous on the exposed outer coast reefs, more oil was splashed on these sites; likewise, more larvae settled on sites of good wave action, a major factor in the healthy recruitment.

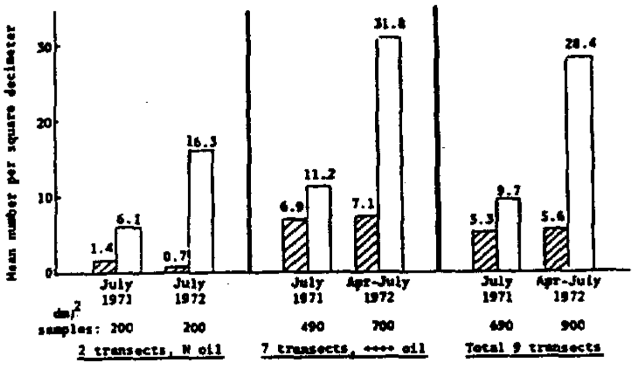

Figure 8. Comparison of *Balanus glandula* and *Chthamalus dalli* for Duxbury Reef, 9 transects

6. Marine Crabs. The shore crab, *Pachygrapsus crassipes*, has not returned to pre-oil densities. Total counts of crabs for Area A berm transects previous to the oil spill had ranged from 30 to 50. Post-oil total counts for this same area ranged from 0 to 2 for 1971 and 1972, and from 1 to 14 for 1973, with some young crabs noted in the July count. The decrease in the crab population is mainly attributable to the oil spill. The present low number is further harassed by hundreds of school children who visit the reef, pick up, and abuse these remnant organisms for a "show and tell" session on the reef. Visitors to this marine reserve must be admonished not to touch these organisms. In area C, *P. crassipes* occupies habitats under the protection of the mussels and appears to be normal in density for this section of the reef.

7. Other Marine Organisms. The starfish population of *Pisaster ochraceus* has declined from pre-oil total counts of 33 to 51 within the transect to post-oil totals ranging from 15 to 32. The July summer counts showed 32 for 1971, 27 for 1972, and 17 for 1973. The drop in number may be due to ecological factors other than the oil spill. Our starfish transect is adjacent to the mussel bed population, which is their chief food source. Perhaps these mobile echinoderms had migrated to areas where mussels did not have oil on the shells. However, in my general assessment of the starfish, the populations do appear normal throughout the Duxbury Reef intertidal and subtidal areas.

Total transect counts for *Lottia gigantea* since 1959 ranged from 16 to 28. In February 1971 all but one of the 22 limpets counted had oil on their shells. A low of 11 in July 1971 may be partially due to the spill. December 1973 showed a high of 34, none of which had oil. The subtle reason why this limpet seems to be increasing may perhaps be its protection from collectors and food hunters due to the marine reserve status of the reef.

Data for other marine species noted in our transect were inconclusive as regards any relationship to the oil spill. The status of post-oil counts is described as compared to pre-oil counts:

Species	Post-oil counts
Anthopleura xanthogrammica, sea anemone	increasing
A. elegantissima, sea anemone	same
Pollicipes polymerus, goose barnacle	increasing
Platyodon cancellatus, boring clam	same
Pholadidea penita, boring piddock	same
Hermaeina smithi, black nudibranch	decreasing
Haliotis rufescens, red abalone	decreasing
Pagurus spp., hermit crabs	same
Pugettia sp., kelp crab	same
Hemigrapsus nudus, purple shore crab	same
Cancer antennarius, cancer rock crab	same
Strongylocentrotus purpuratus, purple sea urchin	decreasing

The establishment of a marine reserve at Duxbury Reef in 1971 has definitely enhanced the population of marine life on the reef. The populations of sea anemones, boring clams, limpets, and snails have escaped the predatory hands of the hunter-collector, man. The decreasing populations of the red abalone *Haliotis rufescens*, the black nudibranch *Hermaeina smithi*, and the purple sea urchin *Strongylocentrotus purpuratus* are all probably attributable to ecological variables surrounding the reef habitat.

We have continued our underwater surveillance of subtidal transects and have concluded that the missing abalones, *H. rufescens*, from these transects have migrated elsewhere to find a more favorable niche. I have not observed any human abalone hunter on this reef for the past three years.

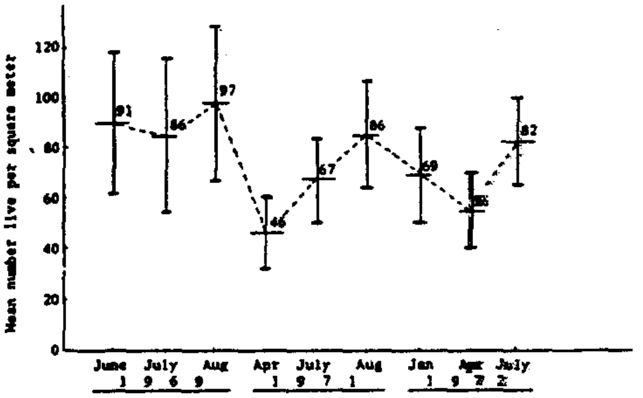

Figure 9. Summary of square meter sampling for all species counted, Duxbury Reef, 13 transects

8. Summary Transects. Figure 9 presents data for 13 transects selected because of corresponding investigation dates. The berm and mussel bed transects are not included in this summary group. Species counted and noted in these summary transects included:

Anthopleura xanthogrammica and *A. elegantissima*, sea anemone
Balanus glandula and *Chthamalus dalli*, acorn barnacle
Pollicipes polymerus, goose barnacle
Pachygrapsus crassipes, striped shore crab
Hemigrapsus nudus, purple shore crab
Cancer antennarius, cancer crab
Pugettia sp., kelp crab
Pagurus spp., hermit crab
Mopalia muscosa, chiton
Mytilus californianus, sea mussel
Platyodon cancellatus, boring clam

Collisella digitalis and *C. scabra*, limpet
Littorina scutulata, periwinkle snail
Tegula funebralis, black turban snail
Acanthina spirata, tooth snail
Pisaster orchraceus, seastar
Strongylocentrotus pupuratus, sea urchin

There was no significant difference between the population means for the species counted of July 1972 as compared to all other summer months for 1969 and 1971 shown in figure 9. There was also no significant difference between the April population means of 1971 and 1972, indicating possible seasonal spring lows attributable to the high mobility of *T. funebralis*, the black turban snail, and to low counts of *Collisella* spp., limpets, and *Acanthina spirata*, marine snail. However, the April 1971 mean was significantly different from all the pre-oil and post-oil summer means, while the April 1972 mean was so for only 3 of the 5 summer means. For this reason, I suspect the April 1971 decline was partially due to suffocation of marine life from the oil spill. April counts should be continually monitored in future years.

CONCLUSIONS

Suffocation by the Bunker C oil was the primary cause of death among marine organisms due to the collision of two Standard Oil tankers on January 18, 1971, which resulted in a 840,000-gallon oil spill in San Francisco Bay. Based on my marine transect studies in several localities, an estimate of 4.2 to 7.5 million organisms, mostly barnacles, had been smothered by the oil, based on an overall 25% dead in the most heavily oil-affected sites. For Duxbury Reef's berm and mussel bed transects, 20% of the sampled organisms were dead, with an extrapolation of some 643,000 to 1,375,000 dead, based on 95% confidence intervals [2]. Now, in April 1974, less than 5% of the oil remains on the rocky surfaces as wave erosion continues to chip away at remnant tar deposits.

The recruitment of marine organisms in the transects has been outstanding for barnacles, mussels, periwinkles, and limpets. In the intertidal areas of Sausalito and Duxbury Reef, the barnacles, *Balanus* spp. and *Chthamalus* spp., and periwinkles, *Littorina scultulata*, have doubled in sample density. Several species of limpets, *Collisella* spp., on the berm of Duxbury Reef, have more than doubled in sample mean, with young limpets less than 1 cm in length to indicate healthy recruitment. The sea-mussel, *Mytilus californianus*, has also nearly doubled in sample counts, and the present population mean is significantly different from pre-oil means. In fact, many small mussels, 2 to 5 cm, can be observed in all my Duxbury transect sites—a good sign of the reproducing capabilities of this mollusk.

The good recruitment of barnacles to the transects simply indicates that planktonic production for these barnacle species has been equal to or higher than that of pre-oil years. Although my study did not deal with the effects of Bunker C on plankton production, the good replacement of barnacles in these study sites leads me to conclude that the Bunker C fuel had little lasting effect on these larval crustaceans. Guard and Cobet [3] also concluded in their study of Bunker fuel that the biologically active hydrocarbons from such spills were removed very quickly in the weathering processes. The remaining oil is simply a very viscous tar, the suffocating agent on the marine life of the intertidal reefs.

Moreover, another reason for good barnacle and limpet replacement may be simply an ecological succession phenomenon. When the eroded oil was chipped off the rocky surfaces, this left much exposed surface for the succession of algae, barnacle larvae, snails and limpets to occupy these open spaces.

On the minus side, there were some decreases in reef organisms. The striped shore crab, *Pachygrapsus crassipes*, which roams on the flat shale of Duxbury Reef, is still below pre-oil counts. My assumption is that many of these crabs were suffocated by the oil. However, the low number may also be attributed to the relentless overhandling by hundreds of students who visit the reefs. Such abuse has been observed many times, despite the enactment of the 1971 marine reserve on Duxbury Reef. The grey periwinkle, *Littorina planaxis*, on the berm of Duxbury Reef seems to be on the verge of extinction. This very small population of about 20 snails was blanketed by oil, and a recent count in April 1974 revealed a seasonal low of two snails remaining.

The summary review of 13 transects (excluding the berm and mussel bed transects) on Duxbury Reef showed a significant decrease of live organisms in the spring of 1971. This drop in marine life density is partially attributed to the mobility of the black turban snail, *Tegula funebralis*, but also reflects the loss of organisms which died from the oil spill. Comparisons of all summer counts for 1969, 1971, and 1972 revealed no significant difference between population means.

The study of marine organisms and the possible relationship of their cyclical patterns to oil suffocation is a very difficult and tenuous task. There are so many ecological variables, such as species differentiation, geological and geographical locations, seasonal biotic and abiotic changes, contaminants from other water sources, and even the differences in the oil morphology, that one may wonder how valid my evaluations are concerning the effects of the 1971 Bunker C oil spill on the marine life within my study transects. By and large, I am confident that my observational studies have been accurate and that they give supportive evidence that large numbers, particularly of the sessile organisms (barnacles), were smothered by the oil residue. The more mobile organisms, such as limpets, snails, and crabs, were afflicted to a lesser extent.

The apparent large overall recruitment of marine organisms to the transects, which includes a healthy replacement of the marine sessile and algal organisms, leads me to conclude that, at this present time, I can see no lingering effects of this Bunker C fuel. Time and the replacement of marine life will restore these intertidal shores to their lush diversity of fauna and flora, providing there is not another catastrophic pollution of one form or another.

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Observations of a Cold-Water Intertidal Community After 5 Years of a Low-Level, Persistent Oil Spill from the *General M.C. Meigs*[1]

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CLARK, R. C. JR., B. G. PATTEN, AND E. E. DENIKE. 1978. Observations of a cold-water intertidal community after 5 years of a low-level, persistent oil spill from the *General M.C. Meigs*. J. Fish. Res. Board Can. 35: 754–765.

A rich and productive intertidal community was exposed continually for over 5 yr to small quantities of a Navy Special fuel oil from the unmanned troopship *General M.C. Meigs* that came aground on the Washington coast in January 1972. Observations of animal and plant populations and their petroleum hydrocarbon uptake patterns showed early evidence of contamination and the persistence of the oil spill throughout the study period. Abnormal and dead urchins, and loss of algal fronds and pigment were observed in localized areas near the wreck for at least 1 yr. Within 2 mo of the accident, paraffinic hydrocarbons had been taken up by prominent members of the community and continued to appear in certain species even after 5 yr. Although changes were seen in certain species during the early days of this persistent low-level pollution incident, the community balance in this rocky, intertidal ecosystem does not appear to have been markedly altered.

Key words: oil spill, hydrocarbons, *General M.C. Meigs*, petroleum contamination, biological effects

CLARK, R. C. JR., B. G. PATTEN, AND E. E. DENIKE. 1978. Observations of a cold-water intertidal community after 5 years of a low-level, persistent oil spill from the *General M.C. Meigs*. J. Fish. Res. Board Can. 35: 754–765.

Une communauté intertidale riche et productive a été exposée continuellement durant 5 ans à de faibles quantités de fuel-oil « Navy Special » provenant du *General M.C. Meigs*, un transport de troupes désarmé qui s'est échoué à la côte de Washington en janvier 1972. Des observations faites sur les populations animales et végétales, et sur les modalités de leur absorption des hydrocarbures du pétrole démontrent qu'il y eut contamination dès le début de la période d'étude et que les effets du déversement persistèrent durant toute la période. Pendant au moins 1 an, nous avons observé des oursins de mer anormaux et morts, ainsi que la perte de frondes et de pigment par les algues dans des régions localisées du voisinage de l'épave. En moins de 2 mo après l'accident, des membres importants de la communauté avaient absorbé des hydrocarbures paraffiniques qui étaient encore présents chez certaines espèces même après 5 ans. Bien qu'on ait constaté des changements dans certaines espèces au début de cette faible pollution persistante, l'équilibre des communautés dans cet écosystème intertidal rocheux ne semble pas avoir été notablement altéré.

Accepted February 13, 1978

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THE unmanned troopship *General M.C. Meigs* (AP-116, 190 m length, 23 m beam, and 7.6 m draft), while under tow from Puget Sound to San Francisco, broke loose and came ashore on the northwest coast of the State of Washington on January 9, 1972. The hull was driven onto a rock pinnacle where it immediately broke into bow and stern sections forming a breakwater that protected "Wreck Cove" from the incoming waves. The fantail then separated from the stern section (Fig. 1). Subsequently the stern section has been progressively ripped apart by wave action until only the mast remains (Fig. 2). The bow section has withstood the pounding of the seas with only a slow loss of its superstructure.

Oil (Navy Special fuel oil) from ruptured fuel tanks

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[1] This paper forms part of the Proceedings of the Symposium on "Recovery Potential of Oiled Marine Northern Environments" held at Halifax, Nova Scotia, October 10–14, 1977.

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FIG. 1. *General M.C. Meigs* aground at Portage Head off Wreck Cove 5 mo after the accident. Size is indicated by the two persons in a raft at lower center.

was released as the stern section of the hulk was ground down onto a submerged rock ledge running parallel to the beach. A major single oil spill occurred during the first 2 d following the accident, and most of the fluid oil came ashore on the shallow rock shelf and intertidal margins of Wreck Cove. Oil released in the form of discrete globules, up to 30 cm diam, has continuously floated into Wreck Cove where it becomes incorporated into the coarse sand beach. Fresh tar globules have been observed for over 5 yr although the individual size and abundance of the globules have diminished with time.

The immediate and short-term effects of the oil contamination resulting from the *General M.C. Meigs* incident on the biota of this rocky shelf ecosystem have been reported by Clark et al. (1973). The recovery of the disturbed areas, as studied from January 1973 to August 1974, was reported in a second paper (Clark et al. 1975) and summarized in a review (Clark and Finley 1977). We are now reporting the results from over 5 yr of visual and chemical investigations of the impact of this persistent, low-level oil pollution on the cold-water marine environment at Wreck Cove. These investigations include assessment of the effects on animal and plant communities, the petroleum hydrocarbon uptake by certain species, and the weathering of the oil that had been released into the study area.

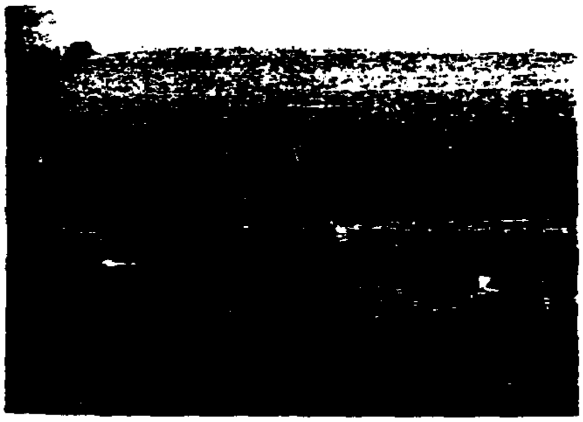

FIG. 2. Remains of the *General M.C. Meigs* 5 yr after the incident showing the relatively intact bow section (*left*) and the aft mast, which had apparently become wedged into a submerged rock reef (*right*). The grounding occurred on the Makah Indian Reservation; the headland in the upper left is being included in the Cape of Arches portion of the Olympic National Park, Washington.

Materials and Methods

ANIMAL POPULATIONS

Long-term changes in the occurrence and abundance of populations of animals and changes in their condition were studied for over 5 yr in Wreck Cove and nearby control areas by making 10 surveys during periods of the lowest monthly tide (Table 1). Methods of making the surveys have been reported (Clark et al. 1973, 1975) but are briefly reviewed here.

The procedure of a survey included (1) making a general inspection of the condition of animals throughout Wreck Cove; (2) enumerating prominent species at predetermined marked sites; (3) making a checklist of fauna found adjacent to a marked site; and (4) photographing prominent communities of animal life to record existing diversity and biomass. Surveys for evidence of oil contamination were confined to Wreck Cove because this was the primary area

TABLE 1. Field investigations at the site of the wreck of the *General M.C. Meigs.*

	Jan. 11, 1972	Feb. 9–10, 1972	Mar. 15–16, 1972	Apr. 18, 1972	May 15–16, 1972	June 12–13, 1972	Aug. 9, 1972	Oct. 20, 1972	Jan. 17, 1973	Feb. 12, 1973	Mar. 9, 1973	June 19, 1973	July 27, 1973	Oct. 25, 1973	Feb. 4, 1974	Aug. 19–20, 1974	Feb. 14, 1977
General observations																	
Visual overview/photographs	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Biological survey	—	×	×	×	×	×	—	×	×	—	—	—	×	—	—	×	×
Animal population counts	—	—	×	×	×	×	—	×	×	—	—	—	×	—	—	×	×
Plant population observations	—	×	×	×	×	×	×	×	—	×	×	×	×	×	×	×	×
Hydrocarbon uptake sampling	—	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

of impact. Observations of the area were made as identical as possible within limitations imposed by the duration of the low tide, the tide height, the height of the storm surf, and daylight. Priority was given to enumerating species at a marked site and making a checklist of fauna adjacent to these sites.

Fifteen sites were selected to include prominent species of animals in each of the intertidal zones of the shelf (Fig. 3). Sites were located along a profile from the upper intertidal (+1.7 m) seaward to the lower tidal zones of the shelf (−0.2 m) (Clark et al. 1973). Each site was marked with a nail driven into the rock substrate with a cement nailing gun. The nails were easily located over the 5-yr period using a map of the beach. Only two nail sites were lost during this period, probably from log or wood debris being dashed against the rock substrate by waves.

At each site, selected animals within a 30 × 30-cm ruled frame that was oriented with a compass were enumerated and photographed. Thus, identical areas at each site were studied on nine surveys. At sites where snails, limpets, and barnacles were studied, they were counted within a specified 10-cm² area within the frame, and mussels were counted within a specified 10 × 30-cm area.

The counting procedure entailed counting the numbers of live and dead small barnacles (*Chthamalus dalli* and *Balanus* sp.), large barnacles (*Balanus cariosus*), and mussels (*Mytilus californianus*) in the frames. Three to five replicate counts of mussels and barnacles were made at four sites to determine counting error. Abundance of the colonial anemone (*Anthopleura elegantissima*) within the frame at site no. 4 was determined by estimating the percent of the substrate they covered.

A checklist of species within 5 m of a site was compiled by identifying animals during the survey or by collecting samples and identifying them later in the laboratory. These species included common, uncommon, and cryptic types (Clark et al. 1973, 1975).

A rock substrate beach at Waatch Point (6.3 km north of Wreck Cove), which supports many of the animals that are present at Wreck Cove, was used as a control site (Clark et al. 1973). Observations (April 17 and June 12, 1972) made at this control site covered only gross aspects of the animal and plant community compared with the studies at Wreck Cove.

PLANT POPULATIONS

A reference algae collection was made from a systematic search at most of the animal population study sites (Fig. 3 Sites 1, 2, 3, 4–7, 8–12, and 13–15). Thirty-seven prominent species of algae were identified (Clark et al. 1973). Initial damage to the plant community was divided into two categories: (1) physical changes to plant structure (loss of fronds) and oil coatings; and (2) chemical changes as evidenced by loss of color ("bleaching").

PETROLEUM HYDROCARBONS

Dominant species of plants and animals that had been exposed to oil contamination from the *General M.C. Meigs* were analyzed and compared with unexposed control specimens of the same species. All samples were chilled for transportation to Seattle and frozen within 16 h. Methods of collection, preservation, preparation, and analysis of intertidal biological specimens to determine uptake of pollutant hydrocarbons have been previously described (Clark et al. 1973; Clark and Finley 1973a; Clark and Finley 1974).

Algae (*Bossiella* sp.) and goose barnacles (*Mitella polymerus*) were extracted after removal of epiphytic algae, endemic organisms, and excess surface water. Mussels were shucked while partly thawed; mussels and goose barnacles were homogenized between extractions (Clark and Finley 1973a). A sample consisted of 3–11 individual organisms depending on the species; weight of a sample varied from 40 to 60 g, wet weight.

The amounts of the *n*-paraffin ($n\text{-}C_xH_{2x+2}$) hydrocarbons were quantified by gas chromatography. Concentrations were expressed on a parts-per-billion (ppb: 10^{-9} g/g) dry extracted-weight basis; i.e. the weight of each individual *n*-paraffin divided by the sum of the weight of the dry residue remaining after removal of the organic material and the weight of the solvent extractables (Clark and Finley 1973a).

Tar globules (usually 4–6 cm diam and several centimetres thick) and scrapings from rocks were stored chilled wrapped in aluminum foil, and frozen on return to Seattle. The samples were extracted 3 times with pentane (approx 1 mL each for sample sizes of 0.5–1.5 g of tarry residue), each time with 1–2-min exposure in an ultrasonic bath. The pentane-solubles were then chromatographed over silica gel and alumina as were the biological samples (Clark and Finley 1973a). The pentane-insoluble residue was then rinsed with three, 1-mL aliquots of 20% (vol/vol) methylene chloride in pentane; this material was chromatographed in a total of one bed volume of this solvent on the same

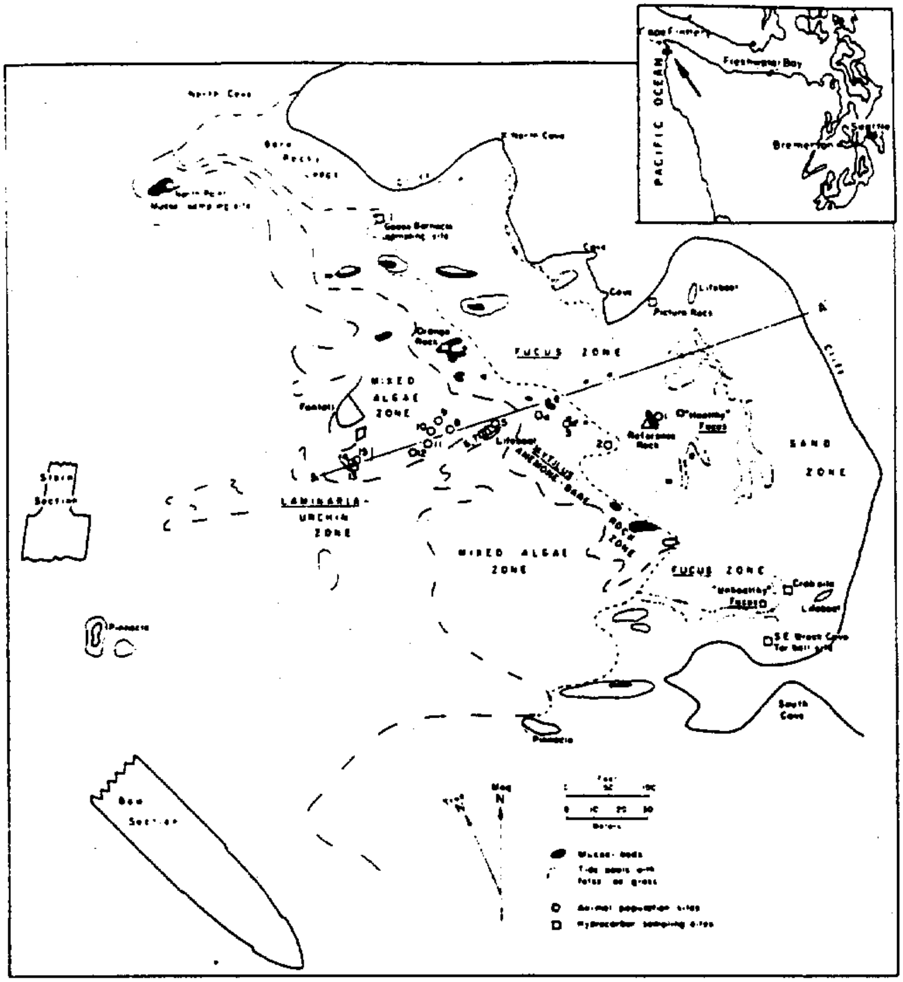

FIG. 3. Wreck Cove showing the animal population study sites and the hydrocarbon sampling sites.

column as for the pentane-solubles. A third set of rinsings followed using pure methylene chloride: the column was stripped with a fourth fraction by percolating through one bed volume of methanol. The last three fractions contained the unsaturated and aromatic hydrocarbons and the polar substances.

Results

ANIMAL POPULATIONS

The initial general survey in February 1972 provided no evidence of recent major damage or extensive animal mortalities. The expected indications of damage such as dead or dying animals, numerous empty mussel or barnacle shells, and bare rock areas showing vestiges of recent life were not evident. Analysis of the count data did not indicate differing ratios of live to dead barnacles or mussels during the period February 1972 to August 1974 (Clark et al. 1973, 1975) or as late as February 1977. However, the abundance of live barnacles, mussels, and the colonial anemones steadily declined from March 1972 to January 1973; the abundance of barnacles had increased by February 1977, whereas the other species remained at an unchanging low level (Fig. 4). Four other species did not have detectable or consistent changes in abundance (Fig. 4).

General surveys made throughout Wreck Cove did not disclose obvious damage to animals except to the purple sea urchin (*Strongylocentrotus purpuratus*). Damaged urchins were found inshore from the stern section at the 0.0 tidal level and below. In March 1972 these urchins had lost spines from the aboral surface, and by April some urchins were nearly aspinous. At some locations up to 70% of the urchins had lost spines from their aboral surface, and the occurrence of broken tests with tissue remaining indicated recent mortalities. Dead or abnormal urchins were not observed at the control sites. Damaged urchins were noted through July

1973, but they appeared normal on subsequent surveys.

None of the 45 animals observed in the species checklist (Clark et al. 1973, 1975) is known to have been eliminated from Wreck Cove or from a specific study site, nor were the numbers of species during any survey considered to be unexpectedly low. Analysis of the photographs did not reveal changes in animal populations.

PLANT POPULATIONS

Physical changes were severe for *Laminaria andersonii* in the area immediately inshore of the stern section; this alga had completely lost its fronds while the stipe and holdfast remained. This damage, which was initially observed several months after the grounding, was still apparent 2 yr later (Clark et al. 1975). Bleached algal tissue was observed within 6 mo of the grounding for a few species of Rhodophyta, notably the intertidal rock and tide pool dwelling plants *Corallina vancouveriensis*, *Prionitis lanceolata*, and *Ceramium* sp., as well as the spermatophyte *Phyllospadix scouleri* (false eel grass) (Clark et al. 1973).

During the summer of 1973 (1½ yr after the incident), the brown alga (*Hedophyllum sessile*) outgrew other algal species to become the dominant alga in the middle intertidal zone of Wreck Cove. By the summer of 1974 (2½ yr later), however, other algae such as *Halosaccion*, *Egregia*, *Desmarestia*, *Gigartina*, *Rhodoglossum*, *Iridaea*, *Codium*, and *Ulva* began to appear in an expected distribution pattern. During the last field observation (February 1977), the early spring development of all plant growth was progressing exceptionally well. False eel grass blades were green and healthy with no traces of necrosis. All new algal growth was crisp and regular. No degradation or attrition of fronds was observed nor was pigment loss noticeable in either thalli or coralline encrustations of the red algae.

HYDROCARBON CONCENTRATIONS IN ORGANISMS

Hydrocarbon patterns have been compared and interpreted for exposed and control samples of algae (*Fucus gardneri*, *Calliarthron schmittii*, and *Bossiella* sp.), false eel grass, purple sea urchins, goose barnacles, purple shore crabs (*Hemigrapsus nudus*), and mussels (Clark et al. 1973; Clark et al. 1975; Clark and Finley 1973b).

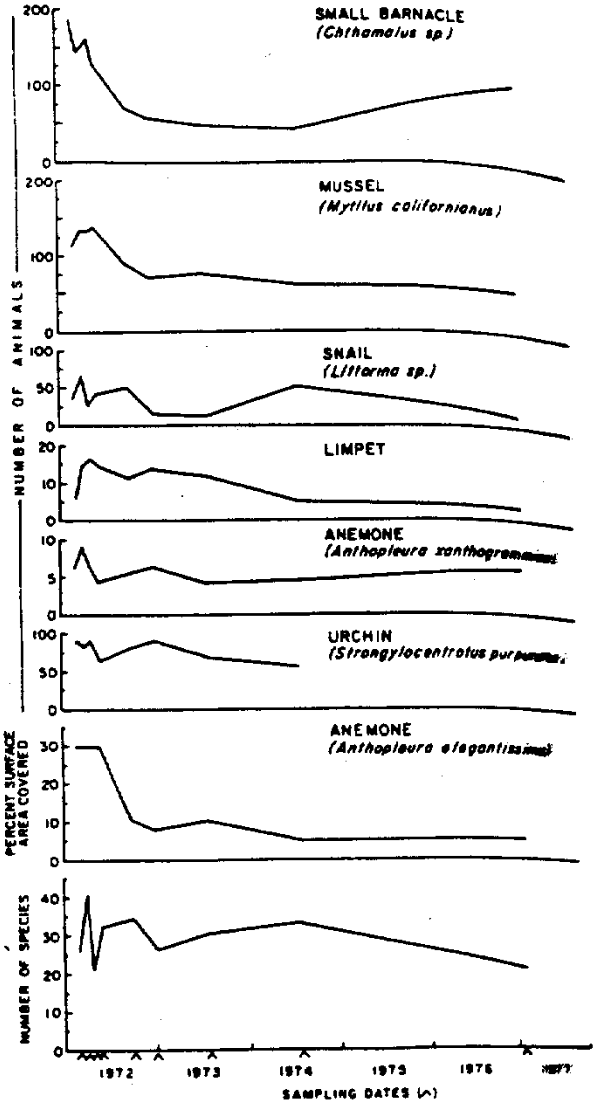

FIG. 4. Abundance of animals in numbers of individuals, percentage of surface area covered, and numbers of species at or near a sampling site during the 5-yr study. The numbers of small barnacles, mussels, snails, limpets, and anemones (*A. xanthogrammica*) are averaged for three to six sites.

Moderate-level hydrocarbon uptake (Fig. 5) was reported for mussels collected and analyzed 2 mo after Navy Special fuel oil leaked from the *General M.C. Meigs* (Clark and Finley 1973b). The *n*-paraffin pattern of mussels collected at the Freshwater Bay control location (Fig. 3) is an average value of two composite samples collected in February of 1972 and 1973. This is assumed to represent the biogenic or environmental hydrocarbon baseline of the mussels. The *n*-paraffin pattern of the exposed organisms (Orange Rock, March 1972; Fig. 3) represents the biogenic baseline plus the pollutant uptake. If the *n*-paraffin pattern of the control samples is subtracted from that of the exposed organisms, the difference constitutes the residual, presumably petroleum-related, *n*-paraffin hydrocarbon pattern. The residual hydrocarbon pattern (Fig. 5B) calculated in this fashion for the mussels and the *n*-paraffin hydrocarbon pattern of a representative beach oil globule sample show similarities beyond n-C$_{1}$[illegible] in the configuration of their patterns (peaks at 20–21, 25, 28, 31, and 34–35 and the troughs at 19, 24, 26–27, 29, and 33). In addition, the residual hydrocarbon content of the

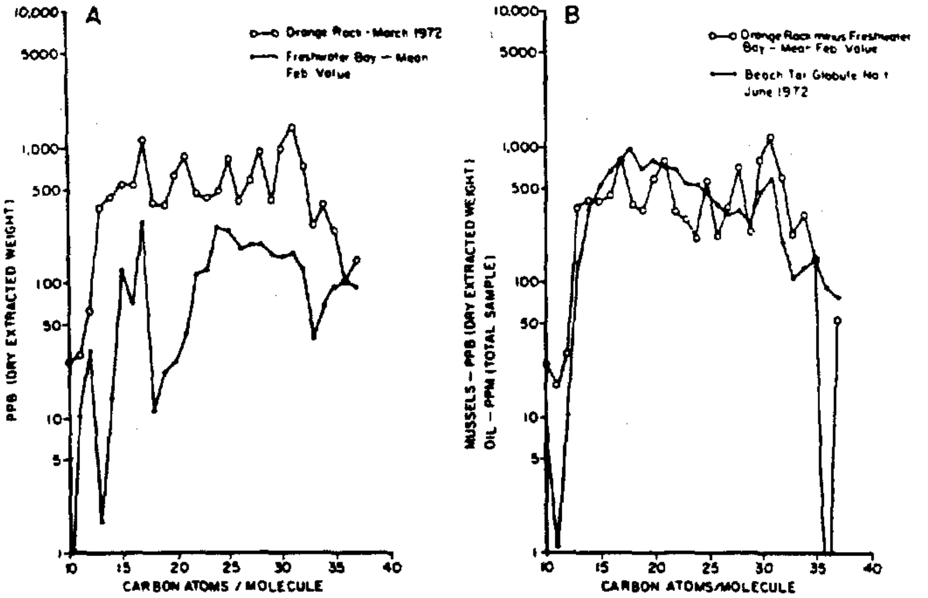

FIG. 5. Paraffin hydrocarbon patterns for mussels (*Mytilus californianus*) exposed to moderate-level oil pollution. (A) Exposed mussels collected at Orange Rock 2 mo after the grounding of the *General M.C. Meigs* are compared with control mussels collected at Freshwater Bay; (B) the residual hydrocarbon pattern is compared with the Navy Special fuel oil residue pattern in a beach tar globule (No. 1, June 1972; Clark et al. 1975).

incorporated *n*-paraffins was from 100 to 1000 ppb. The total residual paraffin hydrocarbon (n-C_{14-37}) content in mussels was 11 ppm which is over 3 times the biogenic content of the controls.

Paraffin hydrocarbon patterns from mussels collected at Wreck Cove 5 yr after the accident are shown in Fig. 6. The Orange Rock samples had a total paraffin content (17 ppm, n-C_{14-37}) twice that of the nearby North Point mussel population (8 ppm); mussels from both areas had paraffin contents greater than the winter average of mussels from Freshwater Bay (3 ppm). The residual hydrocarbon content (Fig. 6B) of Orange Rock mussels was 14 ppm and of North Point mussels was 5 ppm. These residual patterns were similar to one of the two tar globules collected inshore of these sites during the same sampling period (peaks at 17, 21–22, 25, 30–31, and 35 and troughs at 19–20, 23, 26, and 32) although the similarity between the residual patterns and the pollutant is not as apparent as in the 2-mo sample (Fig. 5B).

Analyses of goose barnacles sampled in June 1972 (5 mo after the grounding) and in February 1977 (more than 5 yr after the grounding) at the same site (Fig. 3) showed different hydrocarbon patterns. The June 1972 sample displayed an *n*-paraffin hydrocarbon pattern and content (Fig. 7A) similar to those reported earlier (fig. 11 in Clark et al. 1973). The plot of the 1977 sample, however, shows a considerably different pattern – one that is more similar in shape (Fig. 7B: trough near 19–20 and broad peak at 25–29) and content (Table 2) to samples collected at a site (Mukkaw Bay) remote from known sources of pollution.

One coralline algal species (*Bossiella*, 48 g wet whole weight) collected 5 yr after the grounding had an *n*-paraffin pattern nearly identical to a control sample from Freshwater Bay (81 g wet whole weight; Clark et al. 1975). The analysis of only one other coralline alga, *Calliarthron schmittii* (65 g wet whole weight), obtained 1 mo after the grounding (Clark et al. 1975) suggested that within the 1st mo, the calcified alga did not appear to incorporate measurable concentrations of the pollutant, although other coralline species (such as *Corallina vancouveriensis*) had become bleached.

The unsaturated hydrocarbon fraction from the alumina–silica gel column chromatography separation step (fig. 10 in Clark and Brown 1977) eluted with 20% (vol/vol) methylene chloride in pentane was studied using capillary gas chromatography (MacLeod et al. 1976). Preliminary findings show that the *Bossiella* algae collected in February 1977 had a simple gas chromatogram of the unsaturated hydrocarbon fraction. This chromatogram contained only 46 well-resolved peaks over the retention time range from the methylnaphthalenes to beyond perylene (MacLeod et al. 1976) and displayed a baseline without any unresolved complex mixture envelope (Clark and Brown 1977). Fifteen of the peaks had no corresponding peaks on a complex-appearing gas chromatogram (133 peaks and an unresolved complex mixture envelope above the instrument baseline) seen in a tar globule (No. 1, February 1977) collected at the same time.

In contrast to the gas chromatogram of the rela-

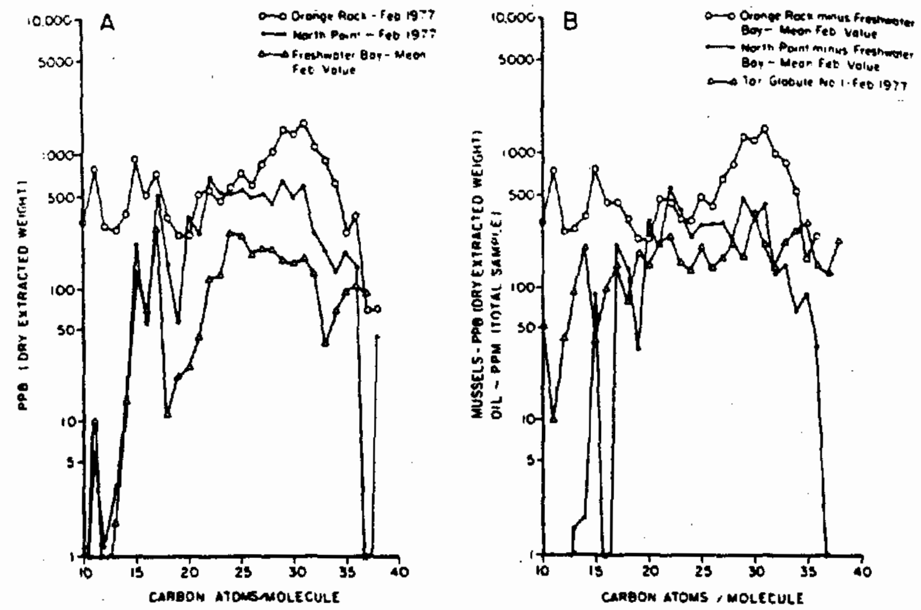

FIG. 6. Paraffin hydrocarbon patterns for mussels (*M. californianus*) collected 61 mo (Feb. 1977) after the grounding of the *General M.C. Meigs*. (A) Samples collected at Orange Rock and North Point are compared with mean February values of mussels from the Freshwater Bay control site; (B) the residual hydrocarbon patterns are compared with a fresh tar globule (No. 1) collected in Feb. 1977.

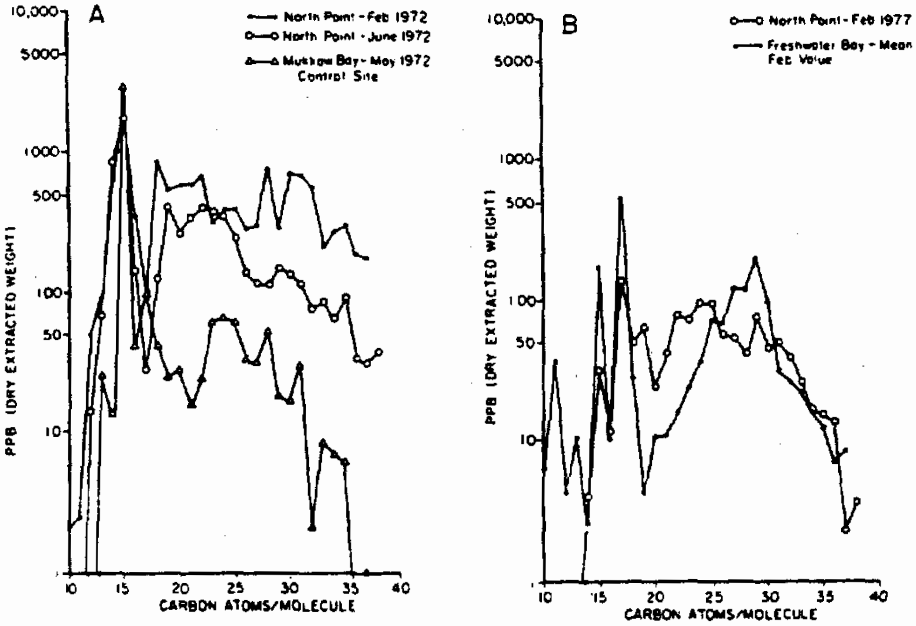

FIG. 7. Paraffin hydrocarbon patterns for goose barnacles (*Mitella polymerus*) from the *General M.C. Meigs* sites are compared with patterns from control samples. (A) Exposed samples from North Point (Feb. and June 1972) are compared with a control sample from Mukkaw Bay, 3 km north (May 1972; Clark et al. 1973); (B) sample from North Point (Feb. 1977) is compared with mean February values of goose barnacles from the Freshwater Bay control site.

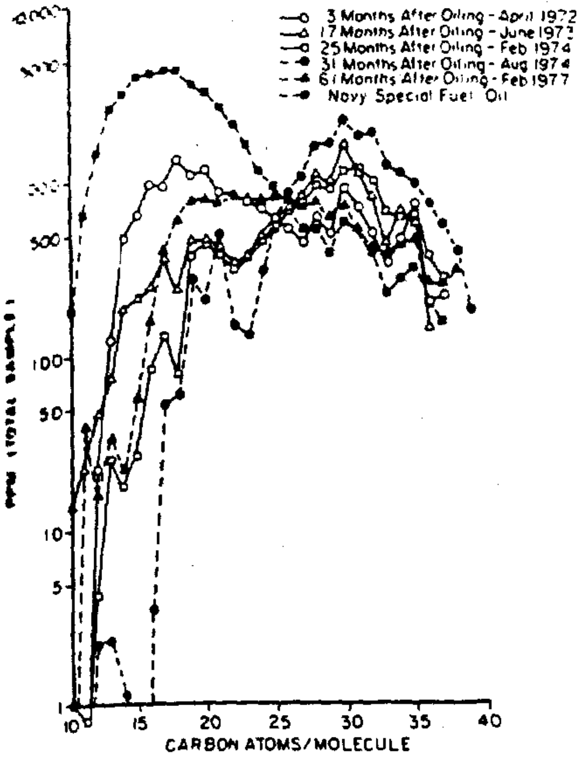

FIG. 8. Paraffin hydrocarbon patterns of Navy Special fuel oil residues after several periods of weathering at Picture Rock.

tively uncomplicated unsaturated hydrocarbon fraction of the alga, the gas chromatograms of the mussel samples collected over 5 yr after the accident displayed complex patterns containing many peaks, unresolved complex mixture envelopes above baseline, and other similarities to tar globule chromatograms. For instance, the Orange Rock mussels had 118 peaks in the methylnaphthalenes–perylene region and the North Point mussels had 107 peaks compared to 133 peaks in the tar globule (No. 1, February 1977). Sixty-seven of the peaks in the Orange Rock mussel chromatogram and 78 in the North Point sample corresponded to peaks in the tar globule.

Extracts from goose barnacles collected 5 mo after the incident gave a gas chromatogram with 134 major peaks appearing above an unresolved complex mixture envelope. A tar globule (No. 2, June 1972) contained 137 major peaks, 123 of which also appeared in the goose barnacle chromatogram. A solvent blank had only three major peaks in the methylnaphthalenes–perylene region. Extracts from goose barnacles collected 61 mo after the initial spill showed no obvious similarity to the tar globules sampled at that time. This recent (February 1977) goose barnacle chromatogram showed a simple pattern with no unresolved complex mixture envelope and a total of only 26 peaks in the methylnaphthalenes–perylene region. All of these peaks corresponded in retention times to peaks in the earlier goose barnacle sample (June 1972) but correlated with only five of the peaks in a tar globule (No. 1, February 1977), which suggests that the recent goose barnacle sample had little, if any, petroleum-related unsaturated hydrocarbon content.

These preliminary findings based on gas-chromatographic retention times are being supplemented by gas-chromatographic–mass spectrometric (GC–MS) examinations of the major individual components using a peak-by-peak correlation between organism chromatograms and tar globule chromatograms. This effort is currently in progress and results will be reported in the future. The results thus far from the unsaturated hydrocarbon fractions, however, closely complement and support the *n*-paraffin hydrocarbon data: (1) the *Bossiella* alga (February 1977) did not display measurable petroleum hydrocarbon uptake; (2) the mussels collected over 5 yr after the accident (Orange Rock and North Point) displayed *n*-paraffin hydrocarbon uptake and complex gas chromatograms similar to tar globules; (3) the goose barnacles collected 5 mo (June 1972) after the accident had *n*-paraffin patterns very similar to previously reported contaminated organisms and the unsaturated hydrocarbon chromatogram had a complex pattern similar to a tar globule collected at that time; and (4) the more recently collected goose barnacles (February 1977) had an *n*-paraffin pattern similar to uncontaminated control samples and a relatively simple (nonpetroleum) unsaturated hydrocarbon gas chromatogram.

PICTURE ROCK TARRY RESIDUES

In the 2 d following the grounding, near-hurricane conditions caused considerable amounts of released oil to be deposited on a rock (Picture Rock, Fig. 3) located about 2.8 m above mean lower low water in the northeast extreme corner of Wreck Cove. Since the oil was well above the usual tide line and only occasionally exposed to the splash from winter storms, oil residues have remained in the cracks and crevices (1–10 mm depth) of the rock for the entire period of observation.

Chemical analyses of the *n*-paraffin hydrocarbon components (Fig. 8) have shown the usual loss of low molecular weight hydrocarbons (Blumer and Sass 1972), but the loss we observed was slow (Clark et al. 1975). The total *n*-paraffin content of the tar scrapings (Table 2) varied between samples as some samples from Picture Rock were thicker than others, depending on crevice depth, and may have weathered less rapidly than thinner scrapings. The pattern for residues collected over 5 yr after the initial oiling showed a distinct loss of lower molecular weight paraffin hydrocarbons and a general smoothing of the paraffin curve over the *n*-C_{20} to *n*-C_{35} region.

TABLE 2. Normal paraffin hydrocarbon data analysis of animals and fuel oil residues from the *General M.C. Meigs* oil spill[a]

Sample analyzed Location collected	Sampling period	Solvent extractables (ppm × 10³)	Total n-paraffin hydrocarbons C_{14-37} ppm	n-C_{17}: pristane ratio	Major hydrocarbon		n-C_{18} ratio	CPI_{14-20}[b]	CPI_{20-36}[b]	Unresolved envelope: n-C.. background
			Mussels (Mytilus californianus)							
Orange Rock (exposed)	Mar. 1972	160	14	1.4	C_{31}	10%	26	1.4	1.1	1.3
Orange Rock (exposed)	Feb. 1977	120	17	2.1	C_{31}	10%	33	1.6	1.1	3.2
North Point (exposed)	Feb. 1977	140	7.9	1.2	C_{22}	9%	150	2.4	1.1	3.1
Freshwater Bay (control)	Feb. Mean	120	2.9	2.4	C_{17}	10%	42	4.4	0.9	1.7
			Goose Barnacles (Mitella polymerus)							
North Point (exposed)	Feb. 1972	24	30	0.09	C_{16}	15%	21	1.2	1.3	4.9
North Point (exposed)	June 1972	23	6.5	0.02	C_{16}	14%	45	3.0	1.1	18
North Point (exposed)	Feb. 1977	17	1.1	0.05	C_{24}	8%	97	3.0	1.1	37
Mukkaw Bay (control)	May 1972	30	3.6	0.01	C_{15}	83%	85	1.1	28	130
Freshwater Bay (control)	Feb. Mean	15	1.7	0.23	C_{17}	32%	170	16	1.3	76
			Petroleum residues[c]							
Tar globule	Feb. 1972	95	7 500	1.2	C_{14}	6%	16	1.0	1.1	2.6
Tar globule No. 1	June 1972	670	8 500	0.96	C_{18}	9%	18	0.8	0.9	2.0
Tar globule No. 2	June 1972	160	9 400	1.2	C_{20}	8%	17	1.1	1.1	2.3
Tar globule	Feb. 1973	200	11 000	0.94	C_{20}	7%	20	1.1	1.0	2.1
Tar globule	Oct. 1973	130	7 600	0.81	C_{20}	7%	19	1.1	1.1	1.9
Tar globule No. 1	Feb. 1977	140	4 900	0.50	C_{30}	8%	50	1.1	1.0	1.6
Tar globule No. 2	Feb. 1977	1100	150 000	2.5	C_{29}	8%	28	1.1	1.1	9.6
Picture Rock	Apr. 1972	600	15 000	2.3	C_{18}	8%	17	0.9	1.0	2.5
Picture Rock	June 1973	530	12 000	1.6	C_{30}	12%	50	1.2	0.9	2.4
Picture Rock	Feb. 1974	490	11 000	0.3	C_{31}	9%	140	1.9	1.0	2.2
Picture Rock	Aug. 1974	500	17 000	0.1	C_{30}	12%	4700	3.0	0.9	1.8
Picture Rock	Feb. 1977	147	12 000	1.2	C_{22}	6%	80	1.2	1.0	2.4
Navy Special fuel oil	1971	950	40 000	1.6	C_{18}	10%	10	1.0	1.0	3.2

[a] All data rounded to two significant figures. A detailed discussion of the application of the parameters presented in this table has been presented by Clark and Finley (1973a).

[b] Carbon preference index (Clark and Finley 1973a).

[c] Pentane-soluble material.

OIL GLOBULES IN THE INTERTIDAL ZONE

Tar globules that appeared fresh were collected in Wreck Cove 5 yr after the accident. However, the Washington coast has been subjected to numerous occurrences of small-scale tar ball pollution in the late spring for the past several years. We were, therefore, interested in whether or not the few tar globules we observed inshore from the *General M.C. Meigs* were still being released from the hulk or if they originated from other sources. Two samples collected in February 1977 had a very similar outward appearance; however, the n-paraffin hydrocarbon patterns and content were very different (Fig. 9). Tar globule No. 1 had a slightly saw-toothed hydrocarbon pattern; a comparable amount of solvent extractables: n-paraffin concentration range of 100–800 ppm; pattern peaks at 25, 30, 35, and 38; pattern troughs at 24, 32, and 36; and carbon preference indices (Table 2) similar to other beach tar samples (fig. 6 in Clark et al. 1975). Tar globule No. 2 collected in Southeast Wreck Cove in February 1977 had 30 times the n-paraffin pattern hydrocarbon content and a much smoother n-paraffin pattern than tar globule No. 1 (very little of the sawtooth shape), with a broad gradually increasing plateau between n-C_{16} and n-C_2 followed by a rapid logarithmic decrease beyond n-C_{28}.

During every survey of Wreck Cove over the 5-yr period, we observed tar globules that frequently contained pieces of rock, shell, wood, evergreen tree needles, and miscellaneous fibrous materials, both internally and on the surface. Of the 15 tar globules analyzed, n-paraffin patterns were similar with the exception of one sample collected in February 1974 (Clark et al. 1975) that did not display the usual smooth curve below tamination by the tar globules in combination with the persistence of the original large petroleum uptake immediately after the incident. Different species have different mechanisms for accumulation and release of oil (Varanasi and Malins 1977), a fact that might explain the difference in the paraffin hydrocarbon patterns found in goose barnacles compared with mussels, both sampled 5 yr after the accident. We suspect that recontamination by winter discharges of tarry material from the hulk caused the high levels in the mussels. The hydrocarbon pollutant patterns represented by the residual paraffin plots of the organisms reflect the degree of pollution throughout the sampling period.

The weathering of oil residues is dependent on the variations of environmental conditions to which the oil is exposed (Clark and MacLeod 1977); however, most of the weathered oil we sampled showed a basic uniformity in *n*-paraffin hydrocarbon patterns to Navy Special fuel oil.

For instance, the tarry residue on Picture Rock was very slow to disappear because of its location in the upper splash zone, where it cannot be routinely attacked by microorganisms that require an aqueous medium for growth (Karrick 1977). Presumably, the tough coating would be hard to penetrate and would reduce evaporation. The usual loss of low molecular weight hydrocarbons was expected, like that reported by Blumer et al. (1973) for a weathered oil sample on a warm and dry rock on Martha's Vineyard, Mass., which was studied for 15 mo.

We believe that throughout our 5-yr survey we have found newly released residues of Navy Special fuel oil from the *General M.C. Meigs* and that the reasonable similarity of the original paraffin hydrocarbon patterns of the oil to subsequent patterns supports this belief. However, one tar globule collected in February 1977 (tar globule No. 2) appeared to be very different chemically from the other 14 tar globules analyzed over the 5-yr study period. Either a tank containing a very different oil had been ruptured during the winter of 1977 or this globule came from some source other than the *General M.C. Meigs*.

Although the *General M.C. Meigs* incident was a relatively minor spill, based on initial oil loss and type of petroleum involved (Clark and Finley 1977), tangible evidence of damage and pollutant uptake by the intertidal organisms was observed. This emphasizes the sensitivity and vulnerability to pollution of those organisms that are generally considered hardy by virtue of the environmental stresses they normally encounter.

Acknowledgments

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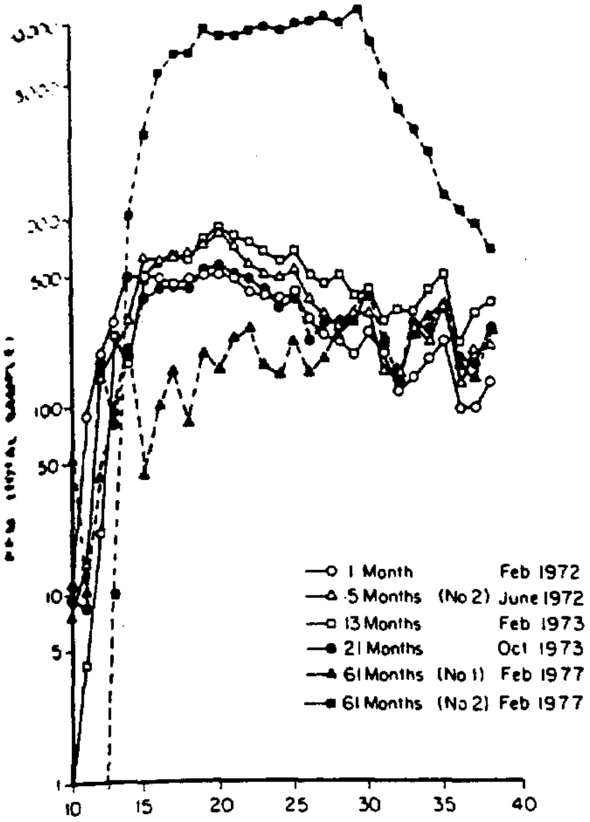

FIG. 9. Paraffin hydrocarbon patterns of fresh oil globules collected in southeast Wreck Cove over a 5-yr period.

n-C$_{22}$ and the one collected in February 1977 described above. The other tar globule (No. 1) collected in February 1977 was somewhat intermediate in character showing some loss of n-paraffin hydrocarbons below n-C$_{25}$ and a slight saw-toothed pattern below n-C$_{20}$.

Discussion

BIOLOGICAL POPULATIONS

The grounding of the troopship *General M.C. Meigs* and the resulting oil pollution exposed sessile animals and plants in Wreck Cove on the Washington coast to oil slicks and tar globules from January to June 1972. After this period, tar globules appeared to be the principal form of contamination throughout the study.

Changes in the number, occurrence, or overt condition of animals in Wreck Cove were not obvious for the 5 yr following the oil spill incident except in the case of the urchins, small barnacles, mussels, and the colonial anemone. Variations that did occur could have been the result of natural fluctuations (Dayton 1971), or changes in the ecology of Wreck Cove caused by the breakwater effect of the remaining hulk. If the oil pollutant had any effect on the animal populations, it was too subtle or localized to be detected by our methods except in the case of the purple sea urchin.

Observations on the damage to the sea urchin coupled with studies on hydrocarbon uptake suggest that oil pollution had affected this animal. During the first 10 mo of observations following the accident, many urchins in localized areas were dead or had lost enough of their spines to make their survival improbable. The behavior of urchins "decorating" their backs with available material of small size in the tide pools resulted in extensive use of fragments of false eel grass for such decoration. False eel grass was one of the species of plants that became coated with oil immediately after the grounding; large quantities of eel grass fragments spotted with tarry residues or bleached white were awash in tide pools in Wreck Cove. Consequently, about 80% of the urchins used false eel grass for decorating themselves immediately after the accident. By August 1974 only about 5% of the urchins still used the false eel grass for decoration; at that time, the eel grass appeared green and healthy. Based on our observations and on the hydrocarbon uptake data (Clark et al. 1975) we can conclude that the only logical reason for damage to urchins was from the oil contamination caused by the *General M.C. Meigs*.

The oil contamination-related damage and deaths of the purple sea urchin were not widespread, and they were outside the site transect (Fig. 3). Therefore, one must not discount the possibility that other less prominent species could have been affected but not detected by our study methods. It is also possible that the behavior of the urchin in decorating itself with pieces of contaminated plant material make it a unique and special case predisposing it to take up considerably more oil pollutants than other animals.

Several species of intertidal plants were seriously affected for several years in Wreck Cove as evidenced by physical changes (loss of fronds and coating with tarry residues) and by chemical changes (loss of pigment and uptake of petroleum paraffin hydrocarbons). Based on the observations from the *General M.C. Meigs* and on other oil pollution studies (Smith 1968; Nelson-Smith 1971; Baker 1971; Baker et al. 1976), intertidal algae may serve as one of the medium term (1–4 mo after the initial short-term animal mortality phase) indicators of petroleum pollution.

CHEMICAL UPTAKE

Our analyses demonstrated that petroleum hydrocarbon residues were present in certain marine animals for at least 9 mo after the initial wreck and oil spill, whereas in specific algal species residues remained for more than a year (Clark et al. 1975). We have now found mussels collected over 5 yr after the accident that contain similar hydrocarbon residues.

The long-term occurrence of contamination in organisms is possibly the result of their periodic recon-

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OIL POLLUTION CONTROL. A COOPERATIVE EFFORT

THE CASCO BAY OIL SPILL: PROBLEMS OF CLEANUP AND DISPOSAL

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ABSTRACT

This paper deals with the control and cleanup of a 100,000-gallon (422,000-liter) no. 6 fuel-oil spill which occurred in Casco Bay, Maine, on July 22, 1972. A lack of locally available equipment, logistics involved in moving men and equipment to numerous offshore islands which were affected by the spill, and disposal of large amounts of oil-soaked debris presented unique problems to on-scene personnel. Additionally, the development of environmental priorities for cleanup proved most critical because the area produces commercial harvests of shellfish, lobsters, and intertidal seaweed, and serves as one of Maine's principal recreation areas.

Of particular concern was the major obstacle encountered in disposing of over 10,000 yards (7,646 m^3) of oil-soaked seaweed which had either been gathered from intertidal rocks or removed from the water surface, and over 4,500 yards (3,440 m^3) of contaminated beach sand. Oil-soaked sand was finally placed in a sanitary landfill utilizing guidelines developed by personnel from EPA, Region I, Solid Waste Program. Oil-soaked debris was incinerated at a facility in Gray, Maine, which was specially modified for this purpose. Modifications included burner head and feed-grate changes to accept the debris.

The damage resulting from the spill and the effectiveness of the cleanup were studied up to one year after the spill, utilizing a private consulting firm under contract to EPA. These studies indicated that the cleanup techniques used resulted in more successful survival and/or recolonization of intertidal populations than in areas not cleaned.

INTRODUCTION

Early in the morning of July 22, 1972, the 810-foot (247-m) Norwegian tanker, *Tamano*, en route to Casco Bay, Maine, struck a submerged ledge in Hussey Sound, an entrance channel to the bay, tearing a hole in the no. 1 starboard wing tank (figure 1). The damage resulted in a spill of a reported 100,000 gallons (422,000 l) of low pour (20°C) no. 6 fuel oil.

Spillage from the incident was not apparent until the ship reached its offshore anchorage, five miles (8 km) from Portland Harbor, approximately forty minutes after striking the ledge when oil was observed escaping from beneath the ship's hull. A local cleanup contractor was immediately contacted by the ship's agent, and he responded with equipment, including containment booms. Concurrently, tank readings were taken on the ship, and an attempt was made to transfer the product from the suspected damaged tank to other tanks aboard the ship. By 5:30 A.M., the ship was partially boomed from bow to midships, and encirclement of the ship with boom was completed by 9:30 A.M. (figure 2).

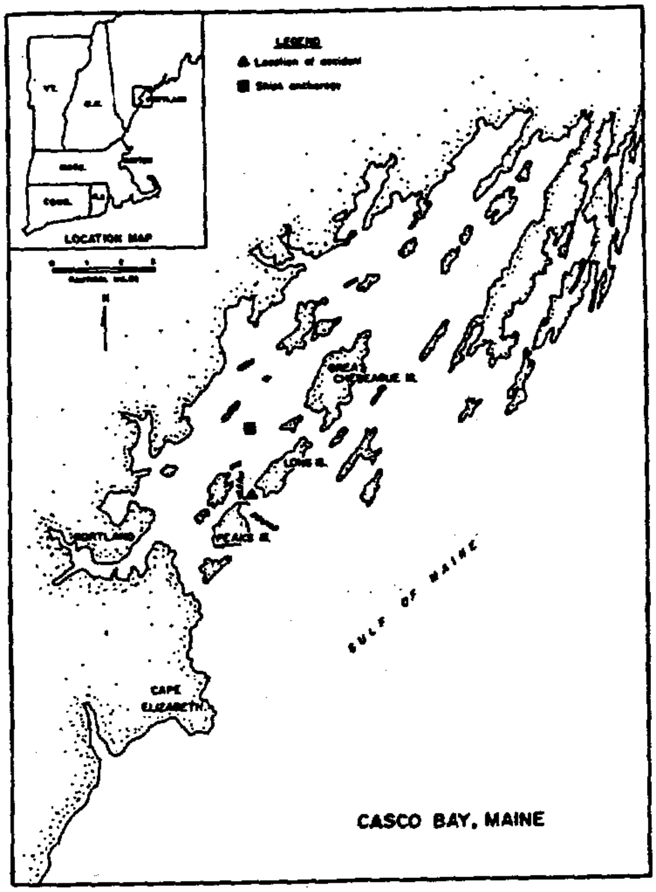

Figure 1. Casco Bay, Maine

Under most circumstances, a stricken ship can be brought into a port area where support facilities are accessible, and the protected nature of the area is more amenable to spill containment and cleanup. This procedure was not available to the *Tamano*, however. A ship of the *Tamano*'s draft (44 ft/13.4 m) cannot enter Portland Harbor's shallow (35 ft/10.7 m) channel depths. Thus, these ships must utilize offshore anchorages for partial or complete offloading. As a result of this limitation, many logistical problems, time delays, and perhaps a wider spread of the pollutant were encountered. In addition, the lack of availability of local equipment to remove oil directly from both the damaged compartment and the boomed area resulted in large losses of oil in the initial period of the spill. This factor, coupled with strong tidal currents prevalent in the bay, consequently affected many miles of shoreline.

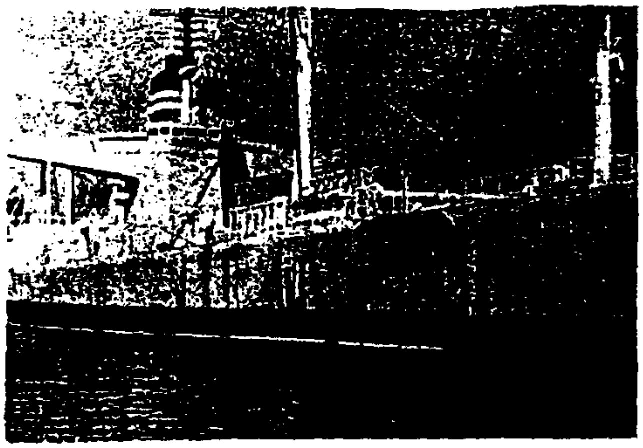

Figure 2. The *Tamano* at anchor

Movement of spilled material and federal/state response

Within eight hours after the spill, personnel from the U.S. Coast Guard, the U.S. EPA, and several agencies in the State of Maine established a control center at the U.S. Coast Guard base in Portland and began coordinating cleanup efforts. Captain D.J. McCann of the U.S. Coast Guard was designated on-scene coordinator (OSC). Primary concern initially centered around three main areas:

1. removal of oil from the damaged tank
2. removal of oil from the boomed area around the ship
3. removal of significant concentrations of oil in the Bay.

Considerable difficulty was experienced initially in transfer of oil at the ship. Locally available pumps that would provide the 50-foot (15-m) head necessary to unload the ship's tank from the top were painstakingly slow. High capacity ADAPTS pumps, operated by the Coast Guard Strike Force were not available at that time; thus, commercial pumps from outside the area had to be brought in.

Oil within the boomed area was removed with skimmers attached to 6,000-gallon (22,710-l) vacuum trucks which were mounted on work barges. Ultimately, two barges, each containing three trucks, were utilized. Oil from this operation and from the damaged tank on board ship was then transferred to tank barges for distribution to shoreside storage tanks.

Heavy oil slicks moving in Casco Bay quickly picked up large amounts of ocean surface debris, which, in some cases, were helpful in absorbing oil but which made removal more difficult. One small paddle wheel skimmer was available at Portland and this was utilized to paravane the oil. Some slicks were treated with hay and corralled with booms for later removal. Other skimmers brought in from the Boston area were also used in removing free oil slicks.

Primarily as a result of the deep-water anchorage, the *Tamano* incident really had many of the characteristics of an offshore spill. This was evidenced by the geographical dispersion of the slicks and the many miles of shoreline affected.

Aerial surveillance during the first day indicated that oil went ashore on the islands immediately seaward of the *Tamano's* anchorage (figure 1). The waterborne oil was quickly dispersed by strong tidal currents, and by the second day, approximately 60% of Hussey Sound was covered with heavy black streaks and rainbow films. Significant quantities had also moved out of the bay into the waters of the Gulf of Maine. Oil remaining in the bay spread concentrically in response to changing tides over the next seven days until 70% of the bay's shorelines was affected. Oil which moved out into the Gulf of Maine traveled southward under the influence of littoral currents, eventually affecting shorelines 33 miles (53 km) south of the spill site. In all, the contamination included 46 miles (74 km) of mainland coastline and 18 islands in Casco Bay [1].

Development of environmental priorities for shoreline cleanup

Casco Bay is typical of the rugged Maine coastline, having been carved by recent glaciation. Intertidal zones are predominated by steep rock shelves, outcrops, and intrusions, interspersed by coarse grained beach areas and few marshes. The tidal range in the area averages nine feet (2.75 m) and the presence of numerous offshore islands constrains tidal movement to channels, resulting in fairly high water current velocities. The bay serves as one of Maine's prime recreation areas. Numerous marinas and many summer and year-round homes dot both the mainland and offshore islands. Additionally, the bay provides a significant resource for the harvesting of shellfish, lobsters, and intertidal seaweeds. The physical characteristics of the area, in addition to its varied usage, presented a formidable task in establishing environmental priorities for shoreline cleanup.

The establishment of such priorities based upon knowledge of environmental effects of pollution discharges and environmental pollution control techniques, including assessment of techniques, has become one of EPA's major roles in coastal oil-spill response.

In order to determine the methods to be used in cleanup, from the standpoint of both feasibility and minimal environmental damage, all shoreline areas affected by the spill were surveyed by EPA and State of Maine personnel. Basically, those shorelines affected by the spill could be characterized into two groups: (1) seaweed covered rocks, and (2) cobble, gravel or sand beaches.

The objective of these surveys was to recommend a cleanup approach which would:

1. mitigate damage already caused by the spill
2. minimize the possibility of producing further damage from the reintroduction of oil to the water column
3. minimize the possibility of causing additional damage by the method of cleanup utilized
4. provide a suitable substrate for the recolonization of cleaned areas by new organisms
5. restore the area as much as feasible to their pre-spill condition.

Obviously, the present technology of shoreline cleanup does not allow the complete fulfillment of all of these objectives. Therefore, the ultimate decisions had to be tempered in terms of:

1. accessibility of the area to cleanup equipment
2. degree of contamination
3. public access to the area
4. potential for recontamination of other areas (especially those of high resource value)
5. physical characteristics of the oil
6. effect and effectiveness of cleanup operations.

Detailed consultations with personnel from the Maine Department of Environmental Protection and the Maine Department of Sea and Shore Fisheries produced valuable information on local conditions and resource areas. Both of these departments were invaluable in assisting in the shoreline surveys and the development of guidelines for shoreline cleanup which were submitted to the OSC for implementation.

The shoreline surveys revealed that in most rocky intertidal areas, the luxuriant seaweed growth which covers the intertidal rocks of the bay had absorbed most of the oil which came ashore (figure 3). Although the degree of contamination varied according to the area in question, representative samples analyzed by the Research Corporation of New England, then performing under contract to EPA, revealed an average oil concentration of 114 gms/kg on seaweed in the more heavily impacted areas [2]. It was thus decided that all heavily impacted seaweed beds would be cropped to insure that these large concentrations of oil would not recontaminate other areas. Holdfasts, which attach individual seaweed fronds to the rocks, were left intact in the hope that more rapid regrowth of the algae would occur.

In areas of public access or of distinct aesthetic value, rocky shorelines were also cleaned using high-pressure hot-water hoses (figure 4). The cleaning system used produced water temperatures of 150-170°F (66-77°C) at 800-1000 psi (56-70 kg/cm^2). Individual areas to be cleaned were boomed off during the operation; sorbents were placed within the boom; and a secondary water source was used to prevent removed oil from settling and recontaminating

Figure 3. Oil soaked intertidal seaweed and rocks

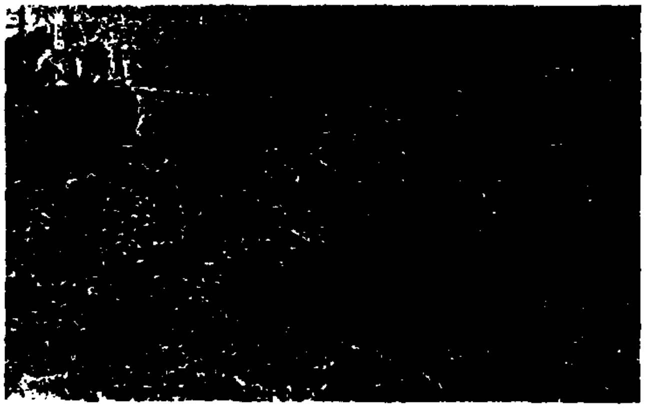

Figure 4. Cleaning intertidal rocks with high-pressure hot water jets

other areas. While this system was effective in removing oil, it proved to be fairly slow and could only be used during lower tidal stages.

Many of the beaches in the Casco Bay area are a considerable distance, 20-40 miles (32-64 km), from the site of the spill. Consequently, by the time oil came ashore in these areas it was well mixed with ocean-surface debris which tended to hold the oil on the beaches' surface, allowing for fairly easy removal. Some of the beaches on the offshore islands were not so lucky. One beach in particular, Western Beach on Long Island, was one of the first shoreline areas affected by the spill. This area is a 2,000-foot (610-m) strip of beach bounded on either end by rock outcrops. It is composed mainly of coarse sand, gravel, and cobbles and is overlooked by many summer homes. Oil was initially deposited on the beach in a ten- to fifteen-foot (3-4.5-m) strip in the upper intertidal area with penetration into sand on the order of one to two inches (2.5-5 cm). As stated earlier, the spilled oil had a pour point of 20°C (68°F). Thus, during periods of low tide when ambient air temperatures exceeded this figure, the oil readily became fluid and moved within the coarse matrix of the beach (figure 5). This characteristic of the oil, in conjunction with the dynamic nature of the beach, resulted in the final contamination of the entire intertidal zone of the beach with penetration averaging four to six inches (10-15 cm), and in some areas as deep as 12 inches (30 cm) (figure 6). Thirty-four core samples of the beach obtained by EPA personnel revealed that oil concentrations in the contaminated area averaged 2.78% of the dry weight of the sand, which conservatively estimated out to slightly over forty thousand gallons (151,400 l) of oil contained in the beach.

Figure 5. Partially cleaned beach area

Figure 6. Test hole showing oil penetration on Western Beach, Long Island

Under normal conditions, upper layers of a beach will tend to be transported offshore during winter months, especially during storm conditions. Thus, the oil contaminated materials of Western Beach would be transported into subtidal areas and be blended into subtidal sediments where further incorporation into the marine food web could take place. This process would be accelerated due to the presence of the oil, as this material fills interstitial spaces in the beach, thus altering its flushing characteristics, and also acts as a lubricant between individual grains. Because of the potential for massive subtidal contamination, and the interference with recreational use posed by the presence of this oil, it was decided that physical removal of the contaminated beach sand was the only feasible means of cleanup. The logistics and mechanics of performing the removal operations presented a unique challenge to on-scene personnel. One of the major problems in conducting such operations was the inaccessibility of the area. The beach is located on one of the offshore islands in Casco Bay which is served by only a small boat dock. This dock is not suitable for handling heavy equipment necessary for the cleanup or for the transfer of the contaminated material. Through the cooperation of the Division of Oil and Special Materials, EPA, Washington, consultants from URS Research Company, San Mateo, California, were brought in to develop specific cleanup methods for this beach.

It was decided that a grounded barge with two cranes on board would be used as a temporary dock, while a bulldozer and dragline would be employed to remove the oil-contaminated sand to stockpile in the backshore area. A front-end loader would move the material from the stockpile onto the grounded barge, and a second barge would be used to transport material to the final disposal site (figure 7) [3]. This system proved quite efficient in overcoming the lack of facilities in the area, and 4,510 yards of contaminated material which comprised an average sand depth of eight inches (20 cm) were ultimately removed. Prior to removal operations, personnel from the U.S. Army Corps of Engineers surveyed the beach to ensure that the removal of these upper layers would not cause erosion problems. In addition, beach profiles were performed on a bimonthly basis for nearly a year following the removal to ensure that the beach remained stabilized (figure 8).

Figure 7. Cleanup operations on Western Beach, Long Island

Figure 8. Western Beach, Long Island after cleanup

Disposal of contaminated materials

A major problem encountered during the *Tamano* spill was the disposal of the vast amounts of contaminated material which had been removed from the affected shorelines. This material included almost 10,000 yards (7,646 m^3) of oil-soaked seaweed and shoreline debris, and over 4,500 yards (3,440 m^3) of contaminated beach sand. No pre-established disposal site capable of accepting this amount of material was available in the Portland, Maine, area, so alternative approaches had to be considered. These included incineration of all material with recycling of the sand, landfilling all material, and landfilling non-burnable material and incineration of burnables.

Total incineration is considered to be the most desirable approach, for once the material is burned, any potential for further contamination is eliminated. After investigation by personnel from EPA and the State of Maine, however, this approach was eliminated since no incinerators were available in New England that could handle the range of materials necessary for this form of disposal. An incinerator was located in Gray, Maine, which would handle the burnable contaminated seaweed and shoreline debris. This incinerator is normally used for burning waste oils and utilizes three in-series burning chambers capable of attaining temperatures of 3400°F. In order to burn the oil-contaminated seaweed, a feed grate was designed utilizing a conveyor arrangement. This system eventually incinerated all of the burnable shoreline material removed in the *Tamano* spill. The cost of disposing of debris amounted to over $70,000.

It was decided that landfill represented the only feasible approach in disposing of the remaining non-burnable material. A number of potential sites were investigated for possible landfill use. The social and political barriers imposed by local governments and the public provided the most serious problem in obtaining a site. Although a number of sites were investigated and appeared to be technically acceptable together with environmental safeguards for disposal, further action was not possible due to local opposition. A site was finally located in the landfill area of the Naval Air Station at Brunswick, Maine. The Navy offered to accept and store the material temporarily at the landfill until it could be used for construction at the base.

The following requirements for site preparation were developed by EPA personnel:

1. A shallow excavation was to be made over the entire disposal area.
2. The entire area was to be surrounded by an earthen dike.
3. The bottom and sides of the area were to be lined with 4-mil polyethylene sheeting.
4. Oily sand and gravel placed in the disposal site were to be mixed with common earth fill in a 50/50 ratio to soak up any loose or free oil.
5. Upon completion of the disposal operation, the entire area was to be covered with polyethylene sheeting and backfilled with dirt.

Once the site was prepared, the contaminated sand was transported by barge from the beach area to the navy base and placed in the disposal area. In June 1974, the Navy reported that they had experienced no leaching or groundwater contamination problem with the material which had been used in part to cover munition bunkers on the base.

It should be noted that the requirements for disposal were not based on previously collected data or experiences, but rather on an engineering judgment. A distinct lack of information and knowledge currently exists with regard to the ultimate disposal of oil-soaked material. This problem perpetually plagues on-site personnel during spill response operations. A much greater research effort is needed to develop site requirements, material preparation, and the pre-establishment of disposal sites dedicated primarily for the disposal of oil and hazardous materials on a regional basis.

Environmental effects and effectiveness of cleanup

Environmental effects of the Casco Bay oil spill and the effectiveness of cleanup methods utilized were investigated by the Research

Corporation of New England under contract to EPA. The purpose of these studies was to first obtain an overview of the impact which this spill had on the marine environment of the area, and, secondly, to determine if cleanup methods were beneficial in mitigating damage and enhancing repopulation of affected areas [4].

The initial phase of these studies consisted of three surveys over a three-month period following the spill. These surveys included biological sampling of affected areas to determine population density, diversity, and chemical examination of intertidal and subtidal organisms and sediments to determine oil concentration and uptake.

The second study phase was conducted one year after the spill and was used to assess the effectiveness of cleanup operations and the longer-term impact of the spill.

Initial surveys showed that the marine communities in the study areas were adversely affected to varying degrees. Intertidal mud flats, which support commercial shellfish beds, were the most heavily impacted. Chemical analyses of both clams and sediments of these areas showed the presence of no. 6 fuel oil. Population density and diversity were severely afflicted with almost complete loss of organisms at one intertidal flat station following the spill and subsequent gradual recovery. Size and frequency analyses of shellfish in contaminated areas showed a complete loss of an early set, which was present at control stations, but apparent resettlement by new spawn following the spill.

Rocky intertidal areas were also severely impacted. An immediate kill of large amounts of seaweed and barnacles in the areas of the greatest oil concentration was evident, and large numbers of periwinkles were found lying upside down in tidal pools. Those organisms that did survive the initial impact of the spill incorporated oil into their tissues. The tissues slowly degraded during the course of the surveys.

Although a shift in population density and diversity was not observed at subtidal stations surveyed, an influx of oil into the sediments was detected and gradually increased in concentration over the course of the surveys. Additionally, lobsters from these areas which initially showed no evidence of fuel-oil contamination had a definite hydrocarbon buildup by the end of the three-month period.

After one year, the affected areas were again studied to determine the longer-term impact of the spill and also the effectiveness of cleanup operations. Generally, intertidal areas were beginning to recover from the effects of the spill. In areas where seaweeds had been killed off, new fronds were beginning to appear, although growth was sparse, and the general density and diversity of species in the intertidal zone had increased since previous surveys. In areas where obvious oil coatings still remained on the rocks, however, new sets of organisms, such as barnacles, did not survive. Length- and frequency-distribution analyses were again conducted on shellfish populations from intertidal mud flats affected by the spill. These analyses showed that while some shellfish in the more heavily impacted areas did survive the spill, no new organisms were present in the contaminated areas. There was, however, a new set of shellfish present in clean areas used as controls in the survey. Thus, it appears that while the marine community of the Casco Bay area is gradually recovering from the effects of the spill, it will be some time before complete recovery can take place.

Cleanup-effectiveness studies utilized, as a standard, the success of recolonization and survival of organisms in those areas that were cleaned compared to those that were not. Of special interest was the effect that seaweed cropping and the use of high-pressure hot water had on the intertidal communities.

In those areas where seaweed had been cropped, regrowth was occurring but was sparse. Populations of organisms normally associated with these algae were still reduced in both numbers and diversity. Surprisingly, seaweed in areas that were not cropped showed remarkable recovery. Apparently, those plants that could survive the initial impact of the spill were able to rid themselves of the oil coating. Thus, it appears that while this cleanup method does successfully remove the pollutant and prevent it from recontaminating other areas, it does cause an additional stress on the environment and should be used only after carefully assessing environmental priorities.

Results of recolonization studies conducted on areas cleaned by high-pressure hot water were somewhat inconclusive. In the upper tidal zone, recolonization in those areas that were cleaned was much less than in areas not cleaned. This area, however, was subject to stress due to public traffic, the effect of which was beyond the scope of the studies. In the lower tidal zone, the use of high-pressure hot water was quite beneficial in aiding repopulation of the area. Populations were much more abundant in these cleaned areas than in corresponding uncleaned areas, and tidal pools in these sites exhibited diverse communities.

While these studies indicated that decisions made in cleanup methodology were basically correct, much more data needs to be collected regarding the effects and effectiveness of cleanup methods presently being used. Only with such data as a base can we validly evaluate the environmental needs and priorities which a particular spill may present, and thus make rational decisions on mitigating damage caused by oil pollution.

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OIL POLLUTION CONTROL. A COOPERATIVE EFFORT

INFAUNAL RECOVERY AT EDIZ HOOK FOLLOWING THE *ARCO ANCHORAGE* OIL SPILL

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ABSTRACT: *The* Arco Anchorage *crude oil spill occurred near Ediz Hook, in Port Angeles, Washington, in 1985. Following the spill, replicate infaunal sampling was carried out during five summer and winter seasons at a series of transects that ranged from relatively clean and unaffected by the spill to industrialized sites that had received heavy oiling. Average wet weight biomass, abundance, species diversity, and number of species were calculated for all samples. Analysis of variance was used to test for differences in these parameters over time within a transect. A statistically significant increase in average biomass, density, and species diversity was seen at several heavily oiled stations over time. A similar pattern was not seen at an unoiled reference station. Biomass, density, and number of species had significant negative correlations with sediment hydrocarbon concentration. A widespread settlement of bivalves was observed in October 1986 samples. Several species from this settlement (e.g.,* Macoma nasuta *and* Clinocardium nuttallii*) were present in successively larger sized classes in subsequent samplings. The industrialized nature of Ediz Hook and pollution events unrelated to the oil spill probably limited the degree of recovery and recolonization documented at several of the transects.*

The December 21, 1985, *Arco Anchorage* crude oil spill and subsequent beach cleanup activities affected intertidal and shallow subtidal habitats along the south-facing shore of Ediz Hook, Washington. A 30-month physical, chemical, and biological monitoring program was implemented by Arco Marine, Inc., at the request of the Washington State Department of Ecology, to evaluate the recovery of that part of Ediz Hook affected by the spill and subsequent cleanup. The organization of the monitoring program team is presented in Miller et al.[12] The physical and chemical monitoring program results are discussed in Miller,[11] and an overview of the spill response and post-spill cleanup is discussed in Mancini et al.[10] This paper presents the results of biological monitoring to document recovery of infaunal populations following the spill and cleanup.

Benthic infauna includes those organisms, primarily invertebrates, that typically live within the upper 30 to 45 centimeters (cm) of the seafloor. Although infaunal communities are most fully developed below the intertidal zone, intertidal infaunal populations can be an abundant and important component of shoreline biota. Infauna are typically sedentary, using a variety of feeding devices to filter food particles out of the water column or remove nutrients from ingested sediments and detritus. Due to their relative immobility and feeding habits, infauna are particularly vulnerable to environmental perturbations such as an oil spill.[13]

Methods

Field sampling. Infaunal communities were sampled at five transects within the Ediz Hook study area (Transects 1, 3, 8, 9, and 11: Figure 1). Samples were collected on five occasions over an 18-month period: in August and October 1986, January and July 1987, and January 1988. The primary sampling effort involved the use of a small hand-held, coring device (with an effective −2 feet mean lower low water datum) to take samples on each of five transects (20 total stations). Sampling transects and tidal elevations had been surveyed previously and located with shore-based benchmarks.[12]

Five replicate small-core samples were collected at each elevation during each sampling period. A meter tape was stretched along the beach contour at each elevation and samples were collected at previously selected random points along the tape. Small-core samples were fixed in buffered formalin prior to laboratory processing.

Samples obtained with the small coring device were passed through a 0.5-millimeter (mm) mesh sieve in the laboratory. Organisms retained on the screen were segregated by major taxonomic group (e.g., clams, crustaceans, and polychaete worms) for enumeration and weighing. Clams, crustaceans, and polychaetes were further identified to the species level by taxonomic specialists.

A large surface area (0.1 m^2) box core sampler was also used during August 1986, July 1987, and January 1988 samplings to collect relatively large bivalves that, because of their size or the depth of their burrow, would not normally be sampled by the small coring device. Three replicate large-core samples were collected at two elevations: +3 and 0 feet. The box core was plunged 30 cm deep into the sediments and the contents scooped out and sieved at 1.25 cm. Bivalves retained on the screen were fixed with buffered formalin.

Data analysis. Tests for differences in infaunal assemblage parameters among sampling periods by elevation within a particular transect were done using one-way analysis of variance (ANOVA). ANOVA is a fundamental statistical method used to test whether two or more sample means could have been obtained from populations with the same parametric mean with respect to a given variable.[15] One-way ANOVAs of polychaete and bivalve density and biomass by sampling period were also performed. A Student-Newman-Kuels multiple range test was used following a significant ANOVA to examine pairs of means. Spearman's rank correlation coefficient was calculated to examine the relation between sediment hydrocarbon concentration (data from Miller et al.[12]) on biomass, density, species diversity, and number of species.

Results

Composition of benthic assemblages. Average total infaunal density, biomass, diversity, and number of species were highly variable within any particular transect over time (Tables 1, 2, 3, and 4). At several stations values for these parameters tended to increase over the course of the monitoring program. However, this trend was not observed at all stations. The parameters also tended to increase with increasing depth: lower beach elevations generally had higher values than did upper elevations. Initial infaunal collections during August

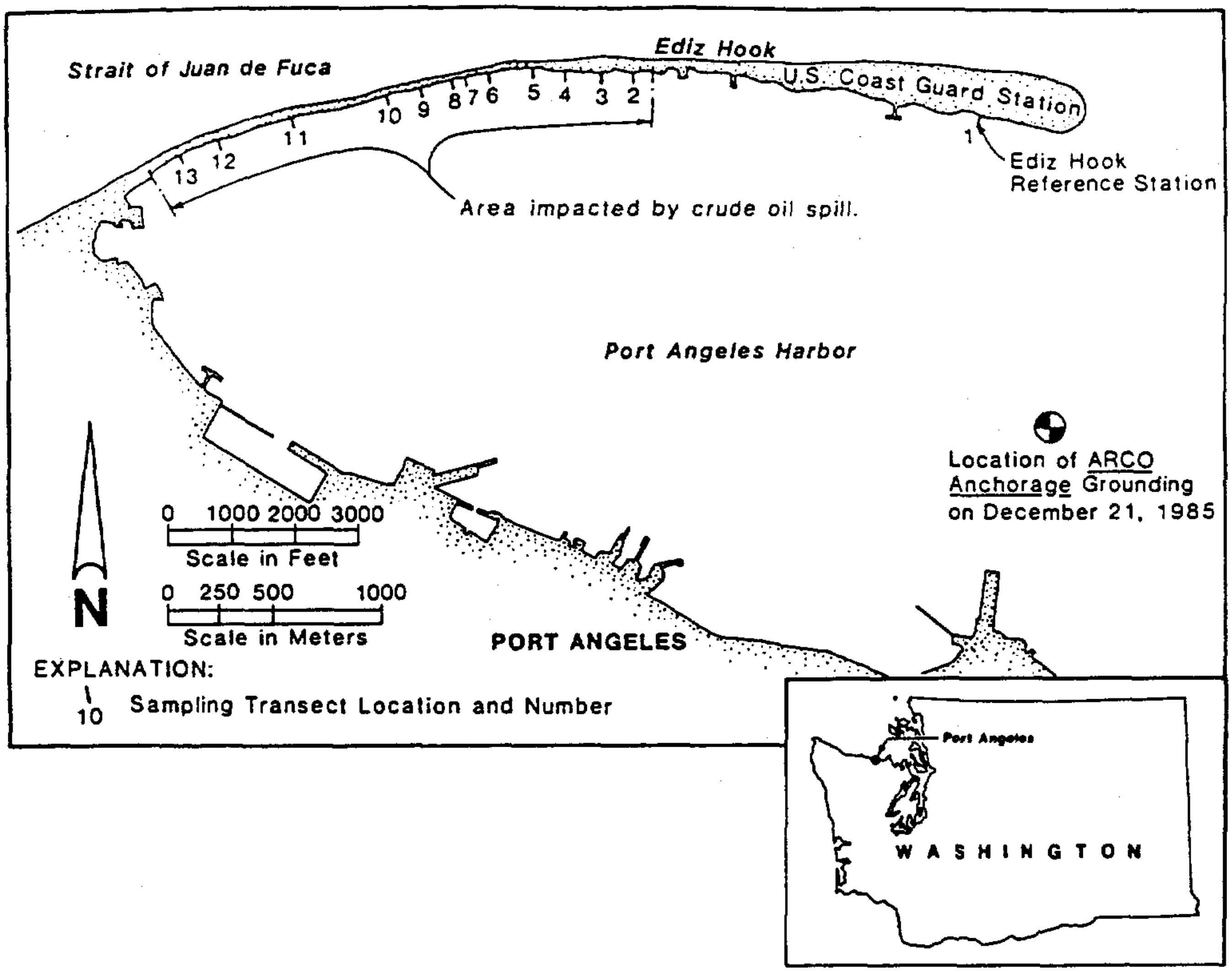

Figure 1. Ediz Hook study area

and October 1986 were dominated by oligochaetes and nematodes at stations that had been heavily oiled. As the monitoring program progressed, the relative abundances and biomass of other groups, especially polychaetes, increased.

Transects within the area of heaviest beach oiling (8, 9, and 11) generally had less diverse infaunal populations than did Transects 1 and 3. This trend was observed in initial sampling periods (August and October 1986) and in subsequent sampling. Transects 8, 9, and 11 have also been affected by previous and ongoing industrial activities. The surficial sediments at these sites, especially Transects 9 and 11, contain relatively large amounts of organic matter (sawdust, bark residue, and wood debris) as well as other types of debris from past industrial activities.

Bivalve and polychaete abundances and biomass within a transect and at a particular elevation were analyzed using analysis of variance. A significant difference in numbers and biomass of polychaetes among the sampling periods was observed at Transects 8, 9, and 11 ($p < 0.05$). In most instances where significant differences were found, the difference was due to relatively higher mean values for the parameter in later sampling periods compared to initial sampling periods. Significant differences in bivalve abundance and biomass among the sampling periods were seen at Transects 8 and 11. The only parameter showing significant differences over time at Transect 3 was bivalve biomass at Elevations +3, 0, and −2 feet; bivalve biomass increased significantly over time at these locations.

A comparison of results from Transects 3, 8, 9, and 11 with Transect 1 (the reference station) showed that similar increases in density and biomass over time generally did not occur at Transect 1. Only polychaete density at 0 and −2 feet showed significant differences over time at Transect 1. Thus, while polychaete and bivalve parameters remained relatively constant over time at the reference station, these parameters increased over time at a number of the stations that had been heavily oiled.

Bivalve recruitment and survival. The combined results of small- and large-core sampling showed that bivalve recruitment occurred during the monitoring program at several of the transects affected by the oil spill and subsequent cleanup activities. Small-core samples from all periods following August 1986 contained small (<10 mm) bivalves. Two periods in particular, October 1986 and January 1988, had relatively high numbers of small (<2 mm) individuals, indicating that a set of bivalves had recently occurred. These recently settled bivalves were dispersed over all tidal elevations between +3 and −2 feet, but generally did not occur at +6 feet. Further, the sets were evident at Transects 1, 3, 8, and 11, but not at Transect 9. An analysis of variance of bivalve biomass at specific elevations within a transect indicated a significant difference among sampling periods with increased bivalve biomass in later sampling periods contrasted with earlier sampling periods at Elevations +3, 0, and −2 feet of Transect 3, Elevations +3 and 0 feet of Transect 8, and Elevation +3 feet of Transect 11. No significant differences in bivalve biomass over time were found in small cores at Transect 1, the reference station.

The large-core sampling showed that adult clams of several species were relatively abundant at Transect 1 throughout the monitoring program (Table 5). Relatively few bivalves were present at Transect

Table 1. Average biomass (g/m²) (±1 standard deviation) of Ediz Hook infauna, by transect and elevation, for all sampling periods

Transect/month	Elevation			
	+6 feet (±1 SD)	+3 feet (±1 SD)	0 feet (±1 SD)	−2 feet (±1 SD)
TR 01				
August 1986	19 (±15)	597 (±506)	2,111 (±854)	281 (±82)
October 1986	21 (±13)	201 (±115)	7,967 (±11,811)	207 (±102)
January 1987	6 (±3)	53 (±37)	394 (±267)	239 (±88)
July 1987	24 (±16)	179 (±224)	473 (±38)	247 (±58)
January 1988	3 (±18)	79 (±77)	1,854 (±1,291)	1,630 (±2,406)
TR 03				
August 1986	3 (±1)	57 (±82)	804 (±727)	178 (±260)
October 1986	221 (±139)	322 (±366)	256 (±105)	1,288 (±1,344)
January 1987	18 (±9)	37 (±13)	179 (±95)	486 (±41)
July 1987	11 (±6)	21 (±4)	164 (±158)	529 (±337)
January 1988	3 (±1)	42 (±7)	515 (±241)	416 (±155)
TR 08				
August 1986	11 (±14)	227 (±65)	44 (±30)	0 (±0)
October 1986	27 (±12)	19 (±23)	528 (±227)	22 (±17)
January 1987	149 (±204)	98 (±56)	240 (±127)	232 (±66)
July 1987	8 (±4)	399 (±102)	145 (±84)	249 (±164)
January 1988	80 (±15)	60 (±59)	297 (±126)	305 (±254)
TR 09				
August 1986	10 (±12)	27 (±39)	22 (±16)	287 (±487)
October 1986	15 (±8)	365 (±111)	60 (±26)	23 (±4)
January 1987	1 (±2)	7 (±4)	2 (±1)	31 (±53)
July 1987	18 (±18)	36 (±28)	8 (±8)	35 (±31)
January 1988	6 (±7)	76 (±52)	7 (±9)	12 (±7)
TR 11				
August 1986	117 (±154)	14 (±15)	77 (±78)	7 (±12)
October 1986	1,101 (±1,112)	1,891 (±1,306)	1,203 (±1,639)	135 (±205)
January 1987	9 (±2)	8 (±9)	141 (±137)	36 (±14)
July 1987	240 (±374)	16 (±6)	108 (±11)	95 (±66)
January 1988	39 (±29)	36 (±29)	201 (±189)	11 (±9)

3 and virtually none were found at the other transects during initial sampling periods. However, during July 1987 and January 1988 large-core sampling, bivalve abundance, biomass, and number of species increased at the 0-foot elevation of Transects 3, 8, and 11 compared to the initial sampling period. Several species of bivalves (primarily juveniles) were represented. For example, at Elevation 0 of Transect 3, 13 *Macoma nasuta*, with an average length of 16.5 mm, were collected in July 1987. In January 1988, 10 *M. nasuta* were collected, with an average length of 29.8 mm. Large adults of this species can reach 110 mm.[4] The same pattern was seen for cockles, *Clinocardium nuttallii*. At Elevation 0 of Transect 3, two cockles with an average length of 16.5 mm were collected in July 1987, and one cockle 28 mm in length was collected in January 1988. Bivalves collected at Transects 8 and 11 did not show a similar pattern of obvious increase in size over time for a particular species. However, both of these transects, which had no bivalves during the initial sampling, contained a number of small clams of several species during the final two large-core sampling periods.

No bivalves were found at Transect 9 during any of the large-core sampling periods, although a few small, recently settled individuals were occasionally found in small-core samples.

Correlation with sediment hydrocarbon concentrations. Both number of species and density showed a significant negative correlation with sediment hydrocarbon concentration; that is, number of species and density were higher in areas with lower sediment hydrocarbon concentrations. These correlations were found both within a sampling period and over the entire monitoring program. Diversity and biomass showed no correlation with sediment hydrocarbon concentration.

Discussion

The benthic community within the Ediz Hook study area was subjected to two major short-term perturbations prior to initial infaunal sampling in August and October 1986: the crude oil spill in December 1985, and subsequent beach agitation through cleanup activities from February through early April 1986.[12] In addition, historical and ongoing industrial activity has affected several of the stations to varying degrees over many years. It can be assumed that near-complete mortality to infauna on Transects 3, 8, and 9 resulted from the combined effects of oiling and beach agitation following the *Arco Anchorage* spill. Transect 11 was affected by oil, but not by beach agitation, while Transect 1 was not affected.

Several investigations of petroleum spills in soft-bottom and mixed gravel-sand habitats in northern latitudes offer some parallels to the *Arco Anchorage* case history. The 1971 spill of No. 2 diesel on Guemes Island in the northern Puget Sound region of Washington caused extensive mortalities of a variety of organisms, including mollusks, bivalves, univalves, starfish, and crustaceans.[20] Although no formal long-term recovery monitoring was done, qualitative observations by one of us (Houghton) in late summer of 1975 revealed a diverse intertidal fauna with no obvious lingering impacts from the spill.

Numerous investigators have reported major reductions of density and diversity of infauna from severely oiled beaches.[2,8,14,16] Some of these areas suffered from repeated oilings and others had additional major disturbance through cleanup activities. In cases where long-term follow-up studies have been reported,[3,14,17] recovery of littoral benthos has occurred at rates that appear to depend on the rate of oil depuration from the sediments. In cases where natural processes have proceeded slowly (e.g., Chedabucto Bay,[17,18] Buzzards Bay[14]), recolonization has been retarded and full recovery not achieved for many years.

Word et al. estimated the time that might be required for Ediz Hook intertidal recovery following the spill as 18.5 months, for sediments to reach background hydrocarbon levels, and nearly four years, for complete biological recovery of the benthos.[21] These estimates assumed a background hydrocarbon concentration of 20 parts per million (ppm) as measured by Brown et al. at the eastern end of Ediz Hook (Transect 1 in this study).[1] Sediment chemistry data from an associated study indicate that residual Alaska North Slope (ANS)

Table 2. Average density (number/m²) (±1 standard deviation) of Ediz Hook infauna, by transect and elevation, for all sampling periods

Transect/month	Elevation			
	+6 feet (±1 SD)	+3 feet (±1 SD)	0 feet (±1 SD)	−2 feet (±1 SD)
TR 01				
August 1986	56.587 (±46,325)	56,772 (±14.719)	245.754 (±120.262)	66.846 (±9,723)
October 1986	18.850 (±6,864)	39,033 (±18,758)	306.006 (±170,323)	46.179 (±2,974)
January 1987	18.035 (±5,264)	30,070 (±1,912)	108.137 (±69.265)	87,770 (±23,479)
July 1987	8,925 (±3,056)	14,999 (±5,124)	45.846 (±9,909)	89,433 (±18.924)
January 1988	10,962 (±4,868)	44,551 (±16,683)	146,135 (±81,291)	72,658 (±24,479)
TR 03				
August 1986	5.629 (±612)	71,771 (±19,285)	193,795 (±138,775)	22,812 (±13.441)
October 1986	96.472 (±43,991)	139,282 (±103,514)	12,803 (±15.541)	153,910 (±89,550)
January 1987	164,650 (±40,804)	146,911 (±24,824)	188.612 (±39,084)	108,363 (±31.458)
July 1987	14,110 (±2,456)	16,146 (±891)	61.919 (±10,899)	120.099 (±35,025)
January 1988	10,443 (±2,589)	46,845 (±17,295)	178.093 (±55,443)	45.105 (±13,638)
TR 08				
August 1986	5,147 (±3,143)	28,516 (±16,189)	52,994 (±8,468)	0 (±0)
October 1986	42,218 (±26,770)	23,886 (±7,690)	123,876 (±121,911)	18,923 (±3,653)
January 1987	46,811 (±26,814)	160,947 (±91,602)	101.103 (±28,950)	100.362 (±40,018)
July 1987	11,592 (±4,584)	34,330 (±12,237)	46,253 (±9,124)	20,442 (±3,079)
January 1988	76,881 (±28,372)	27,812 (±13,714)	103,247 (±29,632)	25,923 (±5,480)
TR 09				
August 1986	22,257 (±14,531)	35,589 (±34,773)	3,999 (±2,613)	3,740 (±4,458)
October 1986	6,480 (±4,311)	142,208 (±20,365)	15,405 (±9,832)	4,147 (±2,126)
January 1987	30,071 (±16,976)	107,471 (±27,664)	20,739 (±12,476)	2,741 (±3,785)
July 1987	10.073 (±7,494)	56,883 (±22,782)	3,703 (±5,265)	8,332 (±6,257)
January 1988	2,037 (±1,079)	88,732 (±44,314)	5,962 (±449)	3,185 (±1.596)
TR 11				
August 1986	54,439 (±38,885)	39,071 (±31,229)	64,512 (±39,293)	1,815 (±1,219)
October 1986	225,237 (±106,482)	273,306 (±130,928)	143,356 (±116,214)	15,294 (±12,708)
January 1987	60,068 (±19,197)	42,959 (±14,802)	50,404 (±10,966)	39,072 (±19,500)
July 1987	48,440 (±38,005)	21,035 (±14,857)	20,071 (±9,323)	14,332 (±11,182)
January 1988	30.885 (±20,292)	51,031 (±33,078)	14,664 (±3,949)	4,777 (±2,057)

Table 3. Average diversity (Shannon Index) of infauna, by transect and elevation, during all sampling periods

Transect/month	Elevation			
	+6 feet	+3 feet	0 feet	−2 feet
TR 01				
August 1986	1.08	1.68	2.04	2.44
October 1986	0.91	1.51	2.60	2.32
January 1987	0.97	1.80	2.44	2.82
July 1987	0.36	1.95	2.48	2.34
January 1988	0.84	1.71	2.78	2.71
TR 03				
August 1986	1.16	0.43	1.50	2.06
October 1986	0.79	0.68	1.75	2.23
January 1987	0.20	0.63	1.32	1.82
July 1987	1.32	1.64	1.80	2.47
January 1988	1.20	1.71	1.85	2.71
TR 08				
August 1986	1.02	1.28	2.18	*empty*
October 1986	0.94	2.07	1.75	1.99
January 1987	0.90	0.77	0.82	1.13
July 1987	0.84	1.60	1.42	1.83
January 1988	1.55	1.71	1.37	1.89
TR 09				
August 1986	0.66	1.03	1.66	0.81
October 1986	1.49	1.17	2.26	2.24
January 1987	0.10	0.73	0.47	0.58
July 1987	1.31	0.85	0.86	0.42
January 1988	1.56	1.00	1.61	1.50
TR 11				
August 1986	0.65	1.01	0.75	0.27
October 1986	1.06	1.92	0.53	1.44
January 1987	0.75	0.96	1.15	1.29
July 1987	1.57	1.19	1.24	0.42
January 1988	1.46	1.49	1.62	0.97

crude oil concentrations in Ediz Hook sediments were below these background levels after July 1987.[11] However, intertidal areas inside Ediz Hook may not necessarily have background sediment hydrocarbon concentrations this low, especially near the heavily industrialized western part (Transects 8, 9, and 11). For instance, MacLeod et al. measured total hydrocarbon concentrations ranging from 170 to 1,530 ppm in 13 intertidal sediment samples near a polluted creek within the Port Angeles Harbor shoreline.[9] If these levels are more indicative of background levels in sediments of the spill area, it is likely that they were reached well before the July 1987 sediment chemistry sampling.

Measurements of ANS crude oil in experimentally treated sediments near Port Angeles showed retention time to be influenced by a number of factors, including initial oil concentration, tidal elevation, exposure of the area to wave activity, and sediment grain size.[19] Retention of oil in sediments during three three-month experiments showed decreases ranging from 20 to 43 percent, from initial concentrations of 1,000 to 2,500 ppm. Data collected as part of the Ediz Hook monitoring program indicate that more than 74 percent of the residual crude oil in the sediments was removed by physical agitation of the sediments during the beach reclamation process. This high percentage decrease in residual concentration occurred approximately four months following the oil spill. Thus, beach reclamation undoubtedly decreased the retention time of oil in the sediments from that expected based on natural weathering processes alone, particularly for deeper sediments (7.5 to 15 cm below the surface).

Several authors have noted that the relative importance of certain tolerant polychaete species often is increased following a spill,[5,14] and the dominance of polychaetes and oligochaetes seen in our 1986 samplings may reflect this tolerance. Reproducing adults of a number of polychaetes, including species that bear their young from capsules on the body surface (e.g., *Exogone lourei*, *Brannia* sp., and *Nothria* sp.) were commonly identified from July 1987 and January 1988 samples, indicating that reproduction was occurring at the sites.[7] Juvenile polychaetes were also commonly observed.

Table 4. Average number of infaunal species, by transect and elevation, during all sampling periods

	Elevation			
Transect/month	+6 feet (±1 SD)	+3 feet (±1 SD)	0 feet (±1 SD)	−2 feet (±1 SD)
TR 01				
August 1986	4 (±2)	5 (±2)	9 (±3)	13 (±5)
October 1986	2 (±0)	8 (±1)	13 (±5)	17 (±4)
January 1987	3 (±1)	12 (±8)	18 (±8)	18 (±2)
July 1987	2 (±1)	7 (±3)	19 (±3)	23 (±5)
January 1988	3 (±1)	6 (±3)	17 (±1)	16 (±2)
TR 03				
August 1986	3 (±1)	4 (±1)	9 (±1)	11 (±6)
October 1986	4 (±0)	5 (±2)	10 (±3)	12 (±2)
January 1987	3 (±1)	6 (±4)	11 (±2)	17 (±2)
July 1987	5 (±2)	4 (±1)	15 (±2)	19 (±3)
January 1988	5 (±2)	15 (±2)	9 (±4)	18 (±3)
TR 08				
August 1986	3 (±1)	4 (±2)	12 (±6)	0 (±0)
October 1986	6 (±2)	8 (±2)	7 (±4)	9 (±2)
January 1987	3 (±2)	5 (±1)	9 (±2)	10 (±4)
July 1987	4 (±1)	7 (±0)	15 (±5)	10 (±4)
January 1988	6 (±1)	8 (±3)	23 (±1)	7 (±1)
TR 09				
August 1986	3 (±2)	3 (±1)	5 (±4)	2 (±2)
October 1986	4 (±0)	3 (±2)	10 (±4)	7 (±2)
January 1987	2 (±1)	2 (±1)	2 (±1)	2 (±2)
July 1987	3 (±1)	2 (±1)	2 (±0)	4 (±2)
January 1988	5 (±0)	4 (±2)	4 (±1)	3 (±2)
TR 11				
August 1986	2 (±0)	4 (±3)	4 (±1)	1 (±1)
October 1986	3 (±1)	6 (±2)	5 (±2)	6 (±3)
January 1987	2 (±0)	4 (±1)	6 (±1)	8 (±2)
July 1987	5 (±1)	6 (±4)	6 (±2)	6 (±4)
January 1988	6 (±2)	10 (±5)	7 (±3)	3 (±1)

Conclusions

Recovery at agitated transects likely occurred much more rapidly than in the absence of beach agitation. In particular, recolonization by bivalves would likely not have occurred as quickly without the documented rapid reduction in sediment hydrocarbon concentrations that occurred following sediment agitation. Bivalves were virtually absent from initial samples in the heavily affected area. Their reappearance in October 1986 samples was due to a widespread settlement throughout the sampling area. Several species from this settlement (e.g., *Macoma nasuta* and *Clinocardium nuttallii*) were present in successively larger size classes in subsequent samplings, demonstrating survival and growth following initial recolonization.

The physical nature of the sediments and industrial activities along

Table 5. Average bivalve density and biomass (±1 standard deviation) and *number of species* for large core samples[1]

	Density (number/m²)			Biomass (g/m²)			Number of species		
Transect/elevation	August 86	July 87	January 88	August 86	July 87	January 88	August 86	July 87	January 88
Transect 1									
+3 feet	3 (±6)	0	—	32 (±55)	0	—	1	0	—
0 feet	20 (±10)	21 (±19)	7 (±12)	2,755 (±1,614)	2,273 (±1,383)	14,410 (±24,958)	2	5	2
Transect 3									
+3 feet	0	0	—	0	0	—	0	0	—
0 feet	30 (±26)	70 (±50)	50 (±69)	123 (±136)	74 (±62)	175 (±280)	2	5	4
Transect 8									
+3 feet	0	0	—	0	0	—	0	0	—
0 feet	0	137 (±108)	67 (±35)	0	252 (±140)	49 (±28)	0	4	4
Transect 9									
+3 feet	0	0	—	0	0	—	0	0	—
0 feet	0	0	0	0	0	0	0	0	0
Transect 11									
+3 feet	0	0	—	0	0	—	0	0	—
0 feet	0	50 (±)	20 (±20)	0	94 (±10)	23 (±23)	0	3	3

1. "—" designates no sample collected at this elevation

the western part of Ediz Hook undoubtedly influence infaunal populations at Transects 8, 9, 11, *and (to a lesser extent)* 3. For example, a depression of infaunal abundance and biomass would be expected in areas subject to wood debris deposition from log-handling activities.[6] This part of Ediz Hook is also subject to periodic episodes of recurring pollution that probably influenced intertidal recovery from the *Arco Anchorage* spill. For example, hydrocarbons from a source other than North Slope crude oil were detected in the sediments in this area after July 1987.[11] This new pollutant source may have influenced assemblage parameters calculated from samples collected during January 1988, when several stations in this area had low biomass (e.g., Elevations 0 and −2 feet at Transect 9).

Infaunal biomass, density, and diversity generally increased over time at transects affected by the spill and subsequent cleanup activities. Given this general increase in infaunal assemblage parameters and the currently low residual ANS crude oil concentrations in the sediments, it is possible that 1988 conditions may be similar to pre-spill conditions. It is also probable that, with ongoing industrial activities and periodic pollution events, infaunal assemblages at Transects 8, 9, and 11 will not show much further development, except for increase in average size for longer-lived species such as bivalves.

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OIL POLLUTION CONTROL. A COOPERATIVE EFFORT

PHYSICAL AND CHEMICAL RECOVERY OF INTERTIDAL AND SHALLOW SUBTIDAL SEDIMENTS IMPACTED BY THE *ARCO ANCHORAGE* OIL SPILL, EDIZ HOOK, WASHINGTON

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ABSTRACT: *The December 21, 1985* Arco Anchorage *crude oil spill affected approximately 7,000 feet of the sheltered, south-facing shore of Ediz Hook, Washington. Some of the stranded crude oil penetrated sand and gravel sediments in the intertidal zone. An aggressive beach agitation program was implemented between February and April 1986 to remove most of the oil trapped within the intertidal sediments. Post-cleanup monitoring activities between August 1986 and January 1988 determined the crude oil content of intertidal and shallow subtidal sediments at five elevations along thirteen sampling transects. Sediment samples were also obtained for laboratory grain-size testing at five of these transects.*

Post-cleanup monitoring of sediment chemistry indicated a consistent trend of decreasing crude oil content of the intertidal sediments between March/April 1986 (mean oil concentration 670 ppm) and July 1987 (mean oil concentration 110 ppm). A similar pattern was observed for the shallow subtidal sediments, where the mean crude oil concentration decreased from 460 ppm in August 1986 to 110 ppm in July 1987. The mean oil content of these sediments increased somewhat after July 1987, indicating probable hydrocarbon inputs from other sources. Chromatograms of the hydrocarbons in the sediments after July 1987 were dissimilar to chromatograms for the unweathered oil from the Arco Anchorage.

The grain-size distribution of the sediments changed relatively little during the post-cleanup monitoring period, reflecting the relatively sheltered nature of the study area. However, the minor changes observed in sediment grain size suggest that gradual redistribution of intertidal and subtidal sediment occurred along the south shore of Ediz Hook during the monitoring program.

On December 21, 1985, the tanker *Arco Anchorage* ran aground in the southeastern portion of Port Angeles Harbor. The grounding ruptured the hull of the vessel, spilling 239,000 gallons of Alaska North Slope (ANS) crude oil.[3] Winds carried floating oil northwest of the spill site, where some of the oil came to rest against approximately 7,000 feet of the south-facing beach of Ediz Hook. Some of the stranded oil penetrated coarse-grained intertidal sediments in an irregular pattern. Even after a surface cleanup of affected portions of the beach, periodic wave action resulted in oil emergence from the sediments and renewed fouling of the beach.

Arco Marine implemented an aggressive beach agitation program to remove most of the crude oil from the intertidal sediments. The beach agitation program was accomplished by bulldozers operating in shallow water with ripper teeth and a water jet system.[4] The beach agitation program was successful in reducing the average crude oil concentration in the intertidal sediments from 2,240 parts per million (ppm) prior to agitation to 670 ppm after reclamation. Some of the intertidal areas affected by the spill were inaccessible to the beach agitation equipment and were not treated by the process.

The fate and effects of the *Arco Anchorage* spill on the south-facing shore of Ediz Hook were documented by a 30-month monitoring program that addressed sediment chemistry, sediment grain size, and infauna (sediment-dwelling organisms). The results of the physical and chemical monitoring of Ediz Hook are presented in this paper. Infaunal studies are summarized in Blaylock and Houghton.[1] An overview of the spill response and post-spill impacts is discussed by Mancini, Lindstedt-Siva and Chamberlain.[5]

Location and setting

Port Angeles Harbor is located in Washington State along the northern coastline of the Olympic Peninsula. Marine waters of the Strait of Juan de Fuca border the northern coastline of the Olympic Peninsula and separate the United States mainland from Vancouver Island, British Columbia. The city of Port Angeles and Port Angeles Harbor are sheltered by a three-and-one-half-mile-long split known as Ediz Hook (Figure 1). This natural split is composed primarily of sand, gravel, and cobbles.[1]

Despite the fact that the natural sediments along the south-facing shore have relatively comparable grain-size distributions at equal tide elevations along the spit, substantial differences exist in physical and environmental conditions within the study area. The east end of the spit is occupied by U.S. Coast Guard Station Ediz Hook (Figure 1). This area was minimally affected by the *Arco Anchorage* spill. The area is closed to the public, is exposed to higher wave energies than more western portions of the spit, and is less affected by industrial activities than areas located west of the Coast Guard station. The portion of the spit between the Coast Guard station and the A-Frame is heavily used by the public and only moderately affected by industrial activity. The A-Frame is used for log loading operations and the intertidal and shallow subtidal sediments in this area are commonly blanketed by, or mixed with, organic debris from the log-handling operations. The A-Frame area was heavily oiled by the *Arco Anchorage* spill. The shore area west of the A-Frame is moderately to heavily impacted by industrial activity and little used by the public.

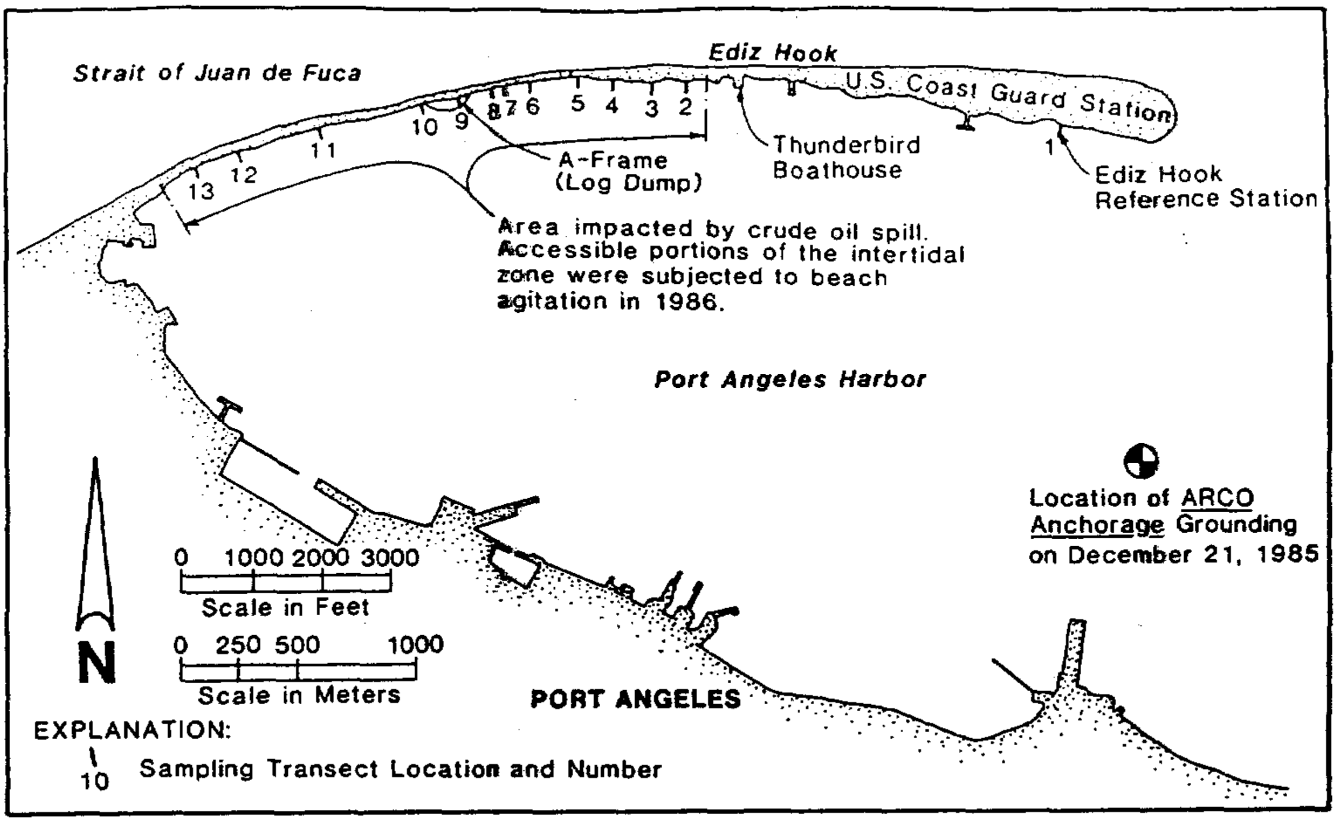

Figure 1. Sampling locations for Ediz Hook monitoring program

Methodology

Sediment chemistry. Post-cleanup monitoring of Ediz Hook sediment chemistry involved repetitive sampling of intertidal and subtidal sediments for ANS crude oil content. Sediment samples were obtained for chemical analysis from 13 sampling transects (Figure 1) according to the schedule presented on Table 1. Samples were collected at five elevations for each sampling transect (+6, +3, 0, −2 and −4 feet, mean lower low water (MLLW) datum). The samples from beach levels +6, +3, 0 and −2 were obtained during low tide by excavating a hole in the sediment with a shovel and collecting sediments to a depth of approximately 12 inches. The samples from Elevation −4 were obtained from a boat using a Shipek surface sampler. Sediment samples were obtained from 65 sampling stations during each sampling period (5 sampling elevations for 13 sampling transects). A sample was not retained for the −4 level of Transect 9 (located at the A-Frame) because this sample consisted entirely of wood chips and bark residue during each sampling period.

For each sampling period, subsamples of beach sediment were collected from seven randomly selected sampling stations. These subsamples were obtained for depth increments of 0–2 inches and 2–12 inches. The purpose of the subsampling was to evaluate whether the very shallow sediment (0–2 inches) was less contaminated than the deeper sediment (2–12 inches).

All sediment chemistry samples collected during the monitoring program were analyzed for ANS crude oil using thin layer chromatography (TLC). Fresh ANS crude oil was used as the analytical standard for qualitative and quantitative identification of concentrations of ANS crude oil in sediment samples.

Approximately 10 percent of the sediment samples analyzed during the Ediz Hook monitoring program by TLC were also analyzed by gas chromatography (GC). The GC analyses on split samples were intended to provide data on the reliability of the TLC analytical method as well as information regarding the degree of weathering of the residual ANS crude oil in sediment at Ediz Hook.

Sediment grain size. Sediment samples were obtained for the purpose of grain-size testing according to the schedule presented in Table 1. The samples were collected from Transects 1, 3, 8, 9 and 11 at Elevations +6, +3, 0 and −2 feet (20 sediment samples for each sampling period). The samples were obtained with a coring device having an end diameter of 11 cm and delivered to the laboratory for grain-size testing.

Sediment samples were visually examined before they were tested. Grain-size determinations were not done on samples that consisted predominantly of wood fiber or organic matter. The samples selected for testing were dried at high temperature with a gas stove to eliminate hydrocarbons and organic matter in the sediment. The sediment samples were then wash-sieved through U.S. Standard screens for grain-size determination.

Table 1. Summary of Ediz Hook field sampling schedule for sediment chemistry and grain size

Type of sampling	Aug. 1986	Oct. 1986	Jan. 1987	Apr. 1987	July 1987	Oct. 1987	Jan. 1988
Sediment chemistry	x	x		x	x	x	x
Sediment grain size	x	x	x		x		x

Notes: 1. Transects 1, 3, 8, 9, and 11 were sampled for sediment grain size.
2. Transects 1 through 13 were sampled for sediment chemistry.
3. Transect locations are shown in Figure 1.

Results

Sediment chemistry. TLC sediment chemistry results are summarized in Table 2. The following spatial and temporal relationships for sediment chemistry were evident at the conclusion of the monitoring program:

- Transect 1 (the reference station on U.S. Coast Guard property) had very low to nondetectable levels of ANS crude in intertidal and shallow subtidal sediments throughout the monitoring program. This transect was not oiled by the *Arco Anchorage* spill.
- For the intertidal zone in areas oiled by the *Arco Anchorage* spill, residual ANS crude oil concentrations were highest at Elevation +6 and lowest at Elevation 0 shortly after conclusions of beach reclamation in 1986. Differences in mean oil concentrations for different intertidal sampling elevations were small at the conclusion of the monitoring program in 1988.
- For the subtidal zone, residual ANS crude oil concentrations were higher at Elevation −4 than at Elevation −2 shortly after beach reclamation in 1986. This pattern generally persisted through the duration of the monitoring program. However, the difference in mean oil concentrations between Elevations −2 and −4 was small after the April 1987 sampling period.
- Residual oil concentrations in subtidal and intertidal sediments were extremely variable spatially. Oil concentrations were below detection limits (50 ppm) for many of the sampling stations.
- Except for the October 1987 sampling period, the average oil concentrations in the shallow sediment depth increment (0–2 inches) of the intertidal zone were less than the average oil concentration in the deeper depth increment (2–12 inches). The ratio of shallow-to-deep average oil concentrations ranged from 0.17 to 0.87 for these sampling periods. The shallow-to-deep average oil concentration ratio was 2.12 for October 1987. This sampling period appeared to reflect the presence of "new" hydrocarbons on the surface of the beach between Transects 9 and 13 during the October 1987 sampling period.
- Average residual ANS oil concentrations in the intertidal zone declined steadily from 670 ppm in March/April 1986 to a minimum of 110 ppm in July 1987. The average intertidal oil concentration increased slightly to 140 and 150 ppm, for the October 1987 and January 1988 sampling periods, respectively.
- Residual oil concentration data for the subtidal zone were not available before or immediately after completion of the beach reclamation activities. Average residual oil concentrations in the subtidal zone declined steadily from 460 ppm in August 1986 to a minimum of 110 ppm in July 1987. The average subtidal oil concentration increased to 410 and 260 ppm for the October 1987 and January 1988 sampling periods, respectively.

Some of the sediment samples analyzed by TLC were also analyzed by GC. Relatively good agreement between the TLC and GC methods resulted until July 1987. The July 1987 chromatograms from the GC analysis of the sediment differed significantly from the chromatograms developed earlier for unweathered ANS crude oil. The chromatograms indicated that by July 1987 very little of the volatile, relatively lightweight hydrocarbons in the crude oil remained in the sediment. Also, the typical chromatogram pattern for crude oil with easily recognizable alkanes and aromatics was not present.

The extensive weathering of residual crude oil in the July 1987 sediment samples made interpretation of the oil concentration in the sediment very difficult by GC. The laboratory standard (unweathered ANS crude oil) was dissimilar from the residual hydrocarbons in the sample extracts. However, reasonable success was achieved in the TLC analyses for July 1987. The TLC method was capable of developing rough estimates of crude oil concentration in sediment even though the residual oil in the sediment was highly weathered in comparison to the original standard.

The TLC analytical technique proved to be a useful method for determining oil concentrations in Ediz Hook sediment, particularly during the first year after beach reclamation activities (when ANS crude oil concentrations were relatively high and before extensive weathering of the residual ANS crude oil). The TLC procedure is nonspecific and detects the presence of most nonvolatile hydrocarbons. Classes of hydrocarbons are separated on the silica gel plates used in the TLC method, providing visual evidence of the hydrocarbons that are extracted from the sediment samples.

The TLC analyses for Ediz Hook samples indicated the presence of hydrocarbon interferences that (1) partitioned on the silica gel plates and were distinguishable from ANS crude oil, and (2) did not partition and were inseparable from crude oil using the TLC method. The TLC oil concentration data presented in Table 2 includes non-ANS interfering hydrocarbons that did not partition on the silica gel plates and excludes materials that partitioned on the plates.

TLC interferences were not a difficult analytical problem until after the July 1987 sampling period. By July 1987 the concentration of residual ANS crude oil in the sediment was generally very low and the residual oil was highly weathered. Sediment contamination by other hydrocarbons was, therefore, more significant and noticeable after July 1987.

The origins of the TLC interferences, whether biogenic or otherwise, are uncertain. Although TLC runs after July 1987 occasionally resulted in high hydrocarbon concentrations when quantitated against unweathered ANS crude oil, subsequent GC runs did not indicate the presence of ANS crude oil in the sediment.

Sediment grain size. The grain-size testing indicated considerable variation in sediment grain-size distribution along the length of Ediz Hook and significant variation by beach elevation. In general, sediment grain size was coarsest near the high tide line and finest in the subtidal areas. Sediments at Elevations +6 and +3 typically consisted of sandy gravel and gravelly sand with occasional cobbles. Gravelly sand was present at Elevations 0 and −2 for Transects 1, 3 and 8. Sediment at Elevations 0 and −2 for Transects 9 and 11 consisted primarily of wood chips, bark residue, and/or fine-grained organic

Table 2. Summary of Ediz Hook TLC sediment chemistry data

Sampling station elevation (MMLW datum)	Mean oil concentration in sediment (ppm)[1]							
	March/ April 1986[2]	March/ April 1986[3]	Aug. 1986	Oct. 1986	April 1987	July 1987	Oct. 1987	Jan. 1988
Intertidal zone								
+6	—	—	840	560	140	180	110	190
+3	—	—	370	130	100	65	125	85
0	—	—	40	50	110	70	190	65
Intertidal average	2,240	670	420	250	120	110	140	150
Subtidal zone								
−2	—	—	130	120	190	100	410	200
−4	—	—	810	570	250	125	405	325
Subtidal average	—	—	460	340	220	110	410	260

1. Concentrations are reported on a wet weight basis with ANS crude oil as a standard. Data for Transect 1 (not oiled by the *Arco Anchorage* spill) are not included.
2. Prior to beach agitation
3. After beach agitation

matter. These organic sediments generally had a hydrogen sulfide odor.

Sediment at Transect 1 was generally coarser than the sediment collected at other transects. The beach at Transect 1 is less sheltered than other transects along Ediz Hook (Figure 1). The coarse nature of the sediments at Transect 1 probably reflects the higher wave energy environment near the eastern end of Ediz Hook.

In general, relatively little change in sediment grain size was noted for specific sampling stations during the Ediz Hook monitoring program. Some of the sampling stations were remarkably stable in their sediment grain-size distributions for the duration of the monitoring program (Transect 1, Elevation +3; Transect 3, Elevation +6; Transect 8, Elevation +6). Relatively stable grain-size conditions were expected due to the sheltered nature of the monitoring area. However, some sampling stations resulted in a variable content of sand and gravel. Transect 1 (Elevation 0) and Transect 9 (Elevation +6) were characterized by more coarse sand and gravel in summer than in winter. Other variations in sand and gravel content could not be correlated with seasons.

Much of the intertidal zone affected by the *Arco Anchorage* spill was "armored" with a surficial layer of cobbles prior to the beach agitation program in 1986. The surface armor layer was most prevalent east of the A-Frame between Elevations +1 and +7.[4] The cobble layer typically had a barnacle encrustation indicating that it was moved very infrequently. The armor layer was breached by the beach reclamation activities that followed the *Arco Anchorage* spill. The surface cobbles became mixed with deeper sediments during the process of beach agitation. The action of the agitation equipment also resulted in ridges of beach cobbles oriented roughly parallel to the shoreline. Photographic documentation indicated little residual evidence of the beach ridges in May 1988. In addition, much of the armor layer was reestablished by this time, two years after completion of the beach agitation program.

Discussion and conclusions

Analytical methods for sediment chemistry. Sediment analysis by TLC and GC proved to be useful and reliable for determining ANS crude oil concentrations during approximately the first 19 months after the *Arco Anchorage* spill. The accuracy of these analytical methods was limited after July 1987 because the laboratory standard used for calculating oil concentrations (unweathered ANS crude oil) differed significantly from the weathered oil and other hydrocarbons that were present in the sediment after mid-1987. The results of the TLC analyses appeared to be less affected by weathering of the oil than the GC results.

Other long-term beach monitoring programs have used a total petroleum hydrocarbon (TPH) analysis using solvent extraction of crude oil from sediments followed by infrared spectrophotometry.[4,7] However, biogenic carbon can influence the TPH analysis and nonrepresentative TPH concentration values can result in areas with significant amounts of biogenic carbon in the sediment.

The intertidal and subtidal sediments at Ediz Hook locally contain high concentrations of hydrocarbons from sources other than the *Arco Anchorage*, as well as biogenic carbon, particularly in subtidal areas located in the vicinity of the A-Frame. Considering the limitations of a TPH analysis for Ediz Hook sediments, the TLC and GC methodology used for the Ediz Hook monitoring program appears to have been reasonable and appropriate.

Trends in oil concentration. The Ediz Hook monitoring program documented a steady decline of residual ANS oil concentrations in intertidal and subtidal areas from March/April 1986 to July 1987. The mean oil concentrations were higher for the October 1987 and January 1988 sampling periods, in comparison with the minimum values determined in July 1987. Elevated concentrations of oil in sediment after July 1987 were found in subtidal and intertidal areas located both east and west of the A-Frame, but not at Transect 1.

Approximately 10 percent of the intertidal sampling stations were subsampled to investigate potential chemistry differences between shallow (0–2 inches) and deep (2–12 inches) sediment. The sampling stations were selected randomly for each sampling period. The mean oil concentration for the shallow sediment was consistently less than that for the deep sediment for all sampling periods except October 1987. Lower oil concentrations in the shallow sediment would be expected due to the increased effectiveness of degradational processes in the near-surface environment. On average, the concentration of oil in shallow intertidal sediment was more than double the deep oil concentration for the October 1987 sampling period. The analytical data indicated a high probability of a source of "new" hydrocarbons to the study area shortly before the October 1987 sampling period in the A-Frame area and west of the A-Frame. The source and character of this "new" material was not determined. This "new" source of hydrocarbons also appeared in subtidal areas for all of the sampling transects, based on increases in oil concentrations detected in subtidal samples during the October 1987 sampling period.

The January 1988 sampling period showed a reduction of oil concentration for most sampling sites compared with October 1987, indicating partial degradation of at least some of the "new" hydrocarbons. However, relatively large increases in TLC oil concentrations were found at several specific sampling stations during the January 1988 sampling period. For instance, the TLC oil concentration for Transect 7 (Elevation +6) was 75 ppm in October 1987. The same station had an 800 ppm TLC oil concentration in January 1988. Relatively large increases in TLC oil concentration values for January 1988 were also detected at several other transects located near the A-Frame and west of the A-Frame. A split sample of sediment from Transect 7 (Elevation +6) was analyzed by gas chromatography for comparison with ANS crude oil. The resulting chromatogram indicated the presence of relatively lightweight hydrocarbons with a chromatogram pattern dissimilar to that of fresh or weathered ANS crude oil.

The increase of mean oil concentrations in Ediz Hook sediment after July 1987 indicated the introduction of other sources of hydrocarbons to the study area in concentrations higher than the residual ANS crude oil. Considering the industrial nature of Port Angeles Harbor and Ediz Hook, periodic spills of petroleum products and the release of other hydrocarbon pollutants would be expected. However, no specific spills in Port Angeles Harbor were reported to the Washington Department of Ecology or the U.S. Coast Guard between July 1987 and January 1988.

ANS crude oil was not identifiable by GC at the conclusion of the monitoring program. The very low (nonquantifiable) amounts of residual ANS crude oil in Ediz Hook sediments at the conclusion of the study were comparable with or less than other hydrocarbon loadings in the sediment.

The beach reclamation activities undertaken at Ediz Hook in early 1986 removed most of the crude oil from the intertidal sediments prior to initiating the monitoring program described herein.[4] The beach agitation process undoubtedly accelerated the rate of degradation of the residual crude oil by reducing the initial oil concentrations and making the processes of evaporation, photo-oxidation, solution and biodegradation more effective. It also appears that the process shortened the time interval needed for successful recruitment of infauna and biological recovery of the area severely affected by the *Arco Anchorage* spill.[1]

Sediment grain-size. The north shore of Ediz Hook has a significant sediment flux due to littoral transport of sediment in a dominant eastward direction.[2] However, the southern, sheltered shore of Ediz Hook has very little input of sediment and is subject to only infrequent storm waves.

The variations in sediment grain-size distributions determined during the Ediz Hook monitoring program indicated that intertidal and shallow subtidal sediments in the sheltered study area are somewhat mobile. No consistent pattern was apparent with regard to changes in sediment texture relative to beach elevation, transect location or season. The shallow sediment is probably mobile relatively infrequently during major storm events. The infrequent mobility of the sediment was sufficient to remove almost all visible evidence of beach agitation by May 1988 and to reestablish the beach armor layer in a similar pattern as that which existed prior to the 1986 beach reclamation activities.

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