The Fate of *Amoco Cadiz* Oil

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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

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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

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.

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.

Oil Chemistry and Weathering

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

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.

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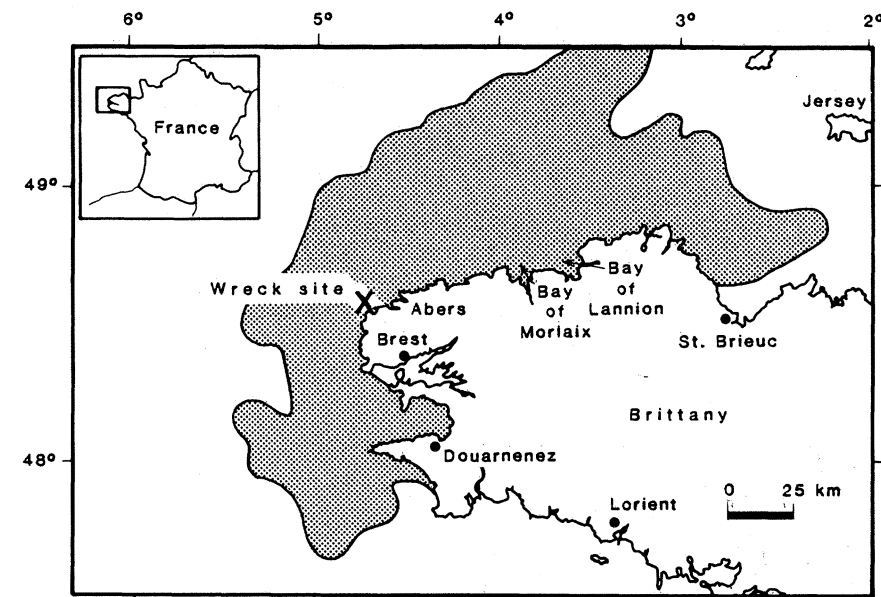
Fig. 1. Maximum distribution of surface slicks between 17 March and 26 April 1978 (11). See Fig. 6 for more detail of the spill-affected shoreline.

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 to 500 μg/liter in Aber Wrac'h and Aber Benoit. These values are comparable to those found at other surface spills [Ekofisk, 30 μg/liter (20); Argo Merchant, 450 parts per billion (ppb) (21); Arrow, 45 ppb (22)] but are much lower than the

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.
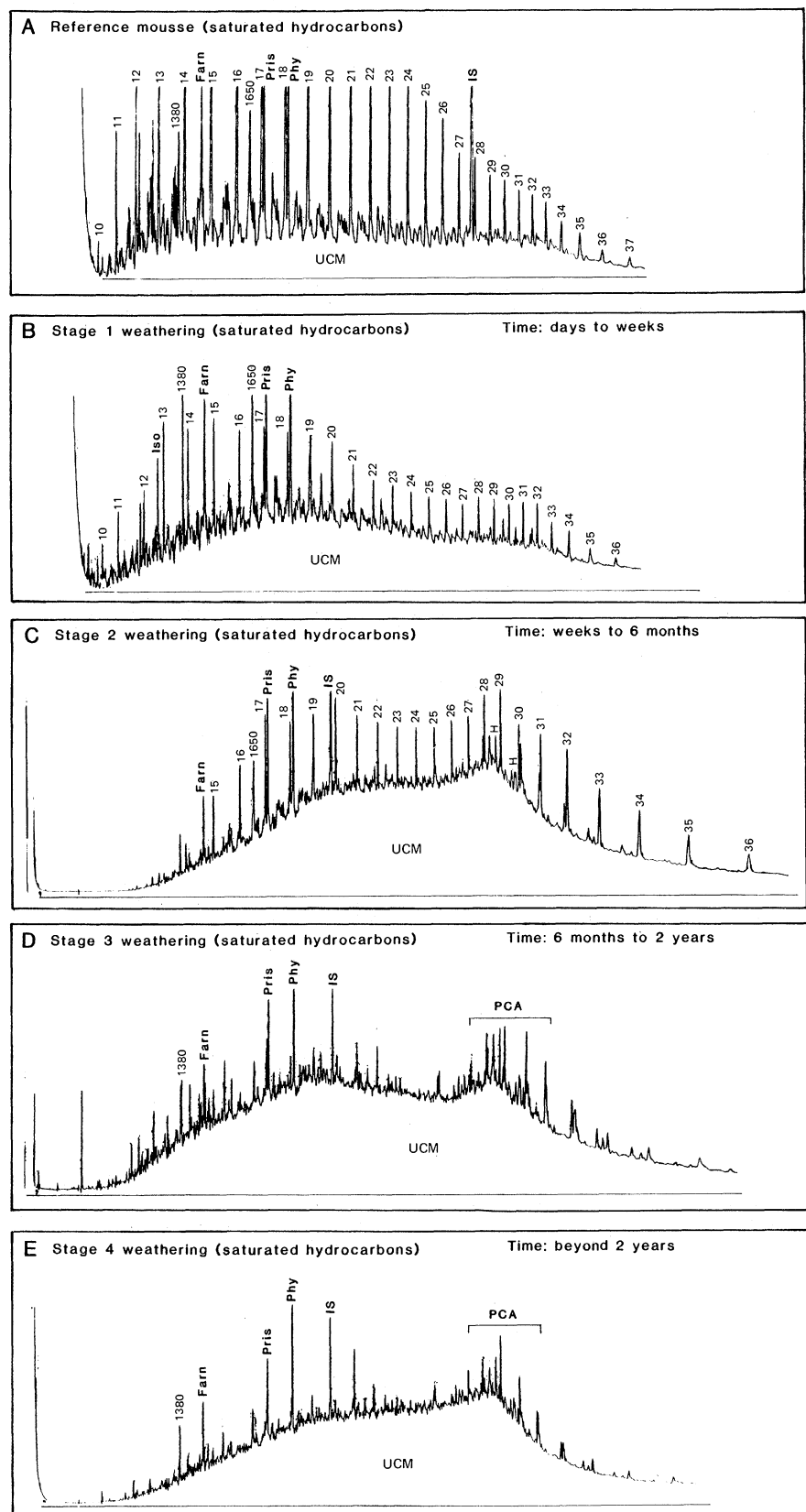

Fig. 2. Capillary gas chromatographic (GC) traces of compositional changes in saturated hydrocarbons of *Amoco Cadiz* oil representative of generalized oil weathering patterns in the oil slick, sediments, and tissues [*10, 11 . . . 37* refer to the number of carbons in *n*-alkanes; *Farn* = farnesane; *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 5I and 6I), 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 the first 3 weeks of the *Amoco Cadiz* spill.

Zone	Depth of mixing (cm)	Area (km²)	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	9,000
Nearshore (shore to 49°N)	30	150 by 30	20	2,700	10,800
Estuaries (Benoit and Wrac'h)	30	12 by 0.3	120	120	16
Total (3 weeks)					19,816

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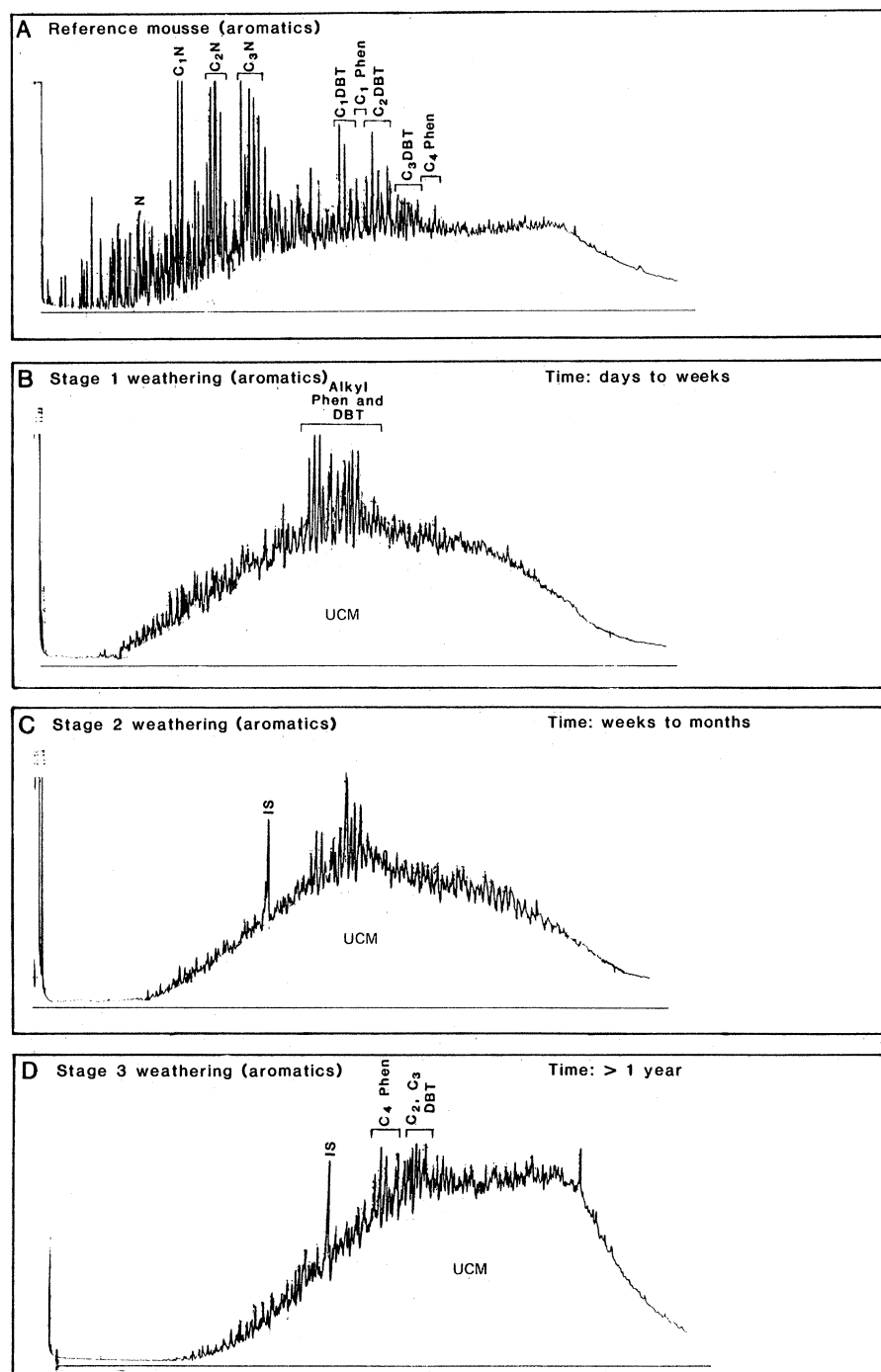

Fig. 3. Capillary GC traces of compositional changes in aromatic hydrocarbons of *Amoco Cadiz* oil representative of generalized oil weathering patterns in the oil slick, sediments, and tissues (N = naphthalene; DBT = dibenzothiophene; $Phen$ = phenanthrene; C_1, C_2, C_3, C_4 indicate the number of 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.

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 slower than under aerobic conditions.
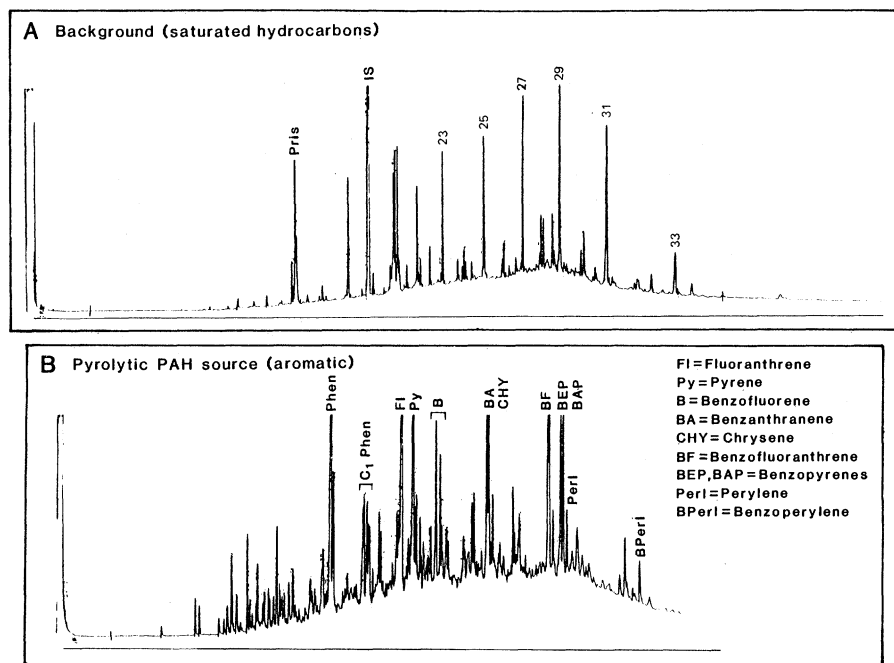

Fig. 4. Capillary GC traces of the typical background hydrocarbon distribution not influenced by *Amoco Cadiz* oil: (A) saturated hydrocarbons (the abbreviations not listed are the same as in Figs. 2 and 3); *IS* = internal standard = androstane; (B) aromatic hydrocarbons (16); *PAH* = polynuclear aromatic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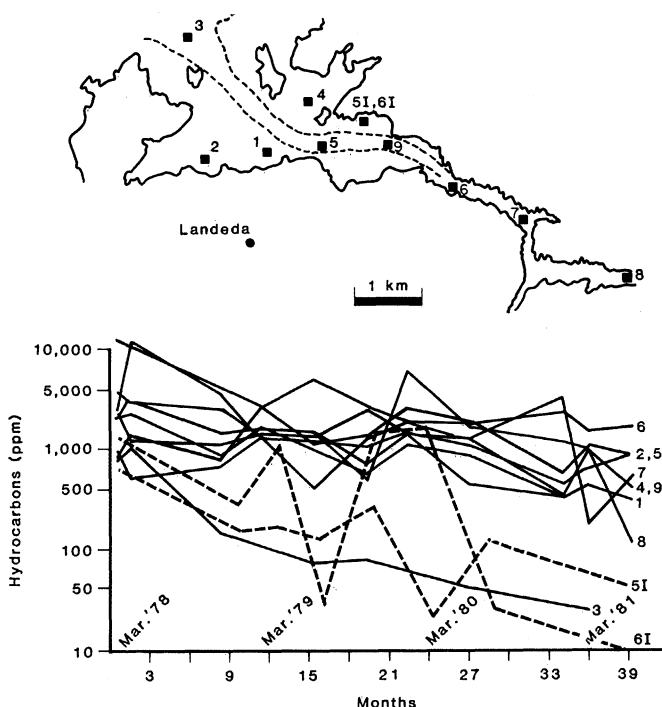

Fig. 5. Hydrocarbon concentrations in Aber Wrac'h sediments from March 1978 through June 1981. Samples at stations 1 through 9 were analyzed by infrared spectroscopy (48); samples at stations 5I and 6I [intertidal (16)] were analyzed by GC.

Biological Effects

The biological and ecological effects of 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 direct readers to the appropriate literature, especially where more recent updates are available (6, 7).

Three principal classes of biologically associated values are subject to impact from oil spills: (i) the commercial market 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 of 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

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 (most 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, soil

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*).

Fig. 6. Initial distribution (March–April 1978) of *Amoco Cadiz* oil along the shoreline (28).
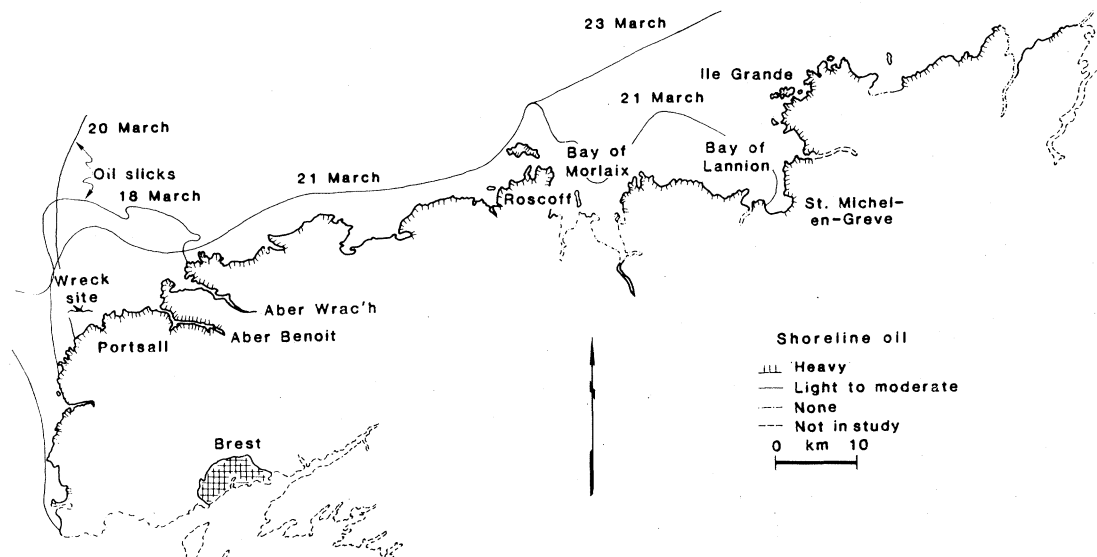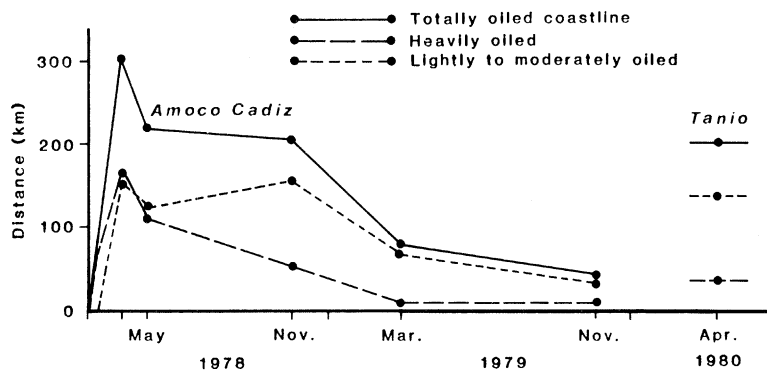
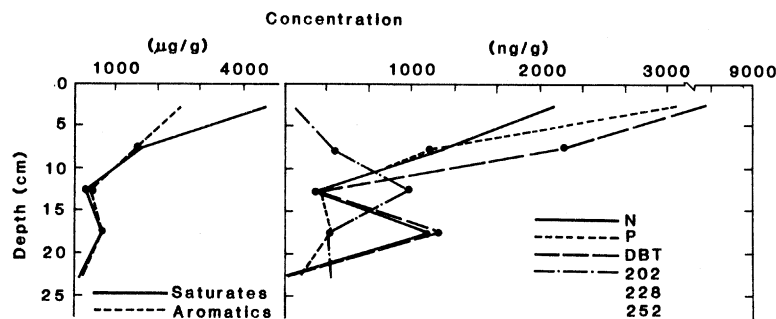Fig. 7. Extent of shoreline oiling from March 1978 to April 1980 (26).

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).
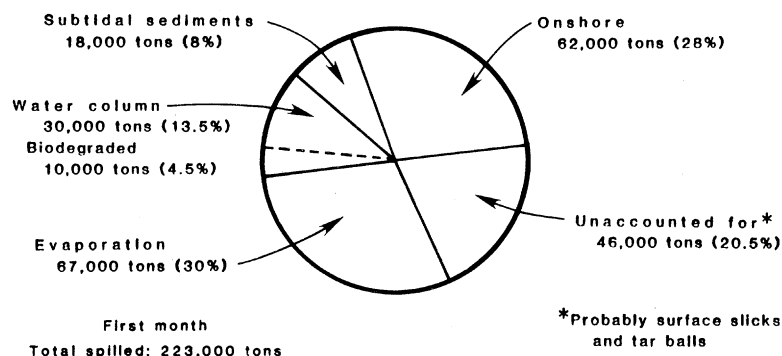

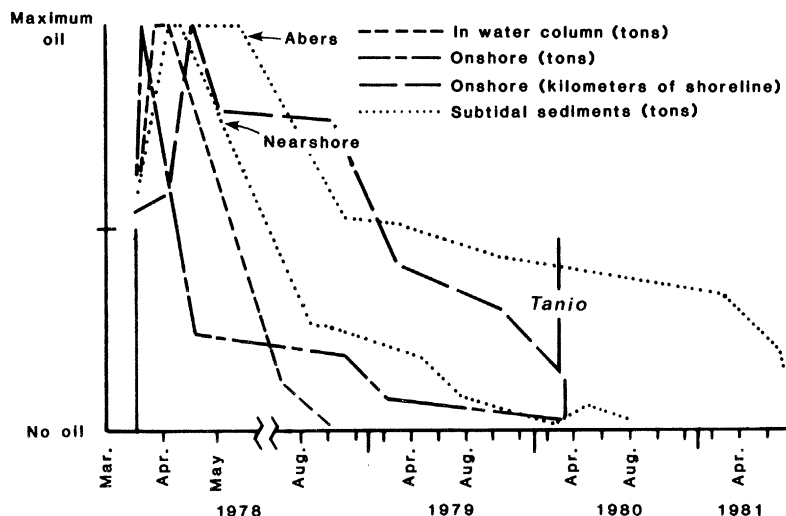Fig. 9. Quantitative estimate of Amoco Cadiz oil dispersal components for the first month of the spill.

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 normal 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 histological changes, thus indicating a probable metabolic transformation of assimilated oil (15). However, residues were readily apparent in oysters although the original Amoco Cadiz oil composition was altered through selective uptake and depuration processes. The most persistent 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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