NOAA/EPA Special Report

The AMOCO CADIZ Oil Spill

A Preliminary Scientific Report

U.S. DEPARTMENT OF COMMERCE / U.S. ENVIRONMENTAL PROTECTION AGENCY
National Oceanic and Atmospheric Administration / Environmental Research Laboratory

NOAA/EPA Special Report

The AMOCO CADIZ Oil Spill

A Preliminary Scientific Report

Edited by Wilmot N. Hess
NOAA Environmental Research Laboratories

Major Contributors:
- Environmental Protection Agency
- U.S. Department of Commerce, NOAA
- Texas A. & M. University
- University of New Orleans
- University of South Carolina

April 1978

U.S. DEPARTMENT OF COMMERCE
Juanita Kreps, Secretary

National Oceanic and Atmospheric Administration
Richard A. Frank, Administrator

Environmental Research Laboratories
Wilmot N. Hess, Director
Boulder, Colorado

U.S. ENVIRONMENTAL PROTECTION AGENCY
Douglas M. Costle, Administrator

Environmental Research Laboratory
Eric D. Schneider, Director
Narragansett, Rhode Island

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

NOTICE

The Environmental Research Laboratories do not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to the Environmental Research Laboratories or to this publication furnished by the Environmental Research Laboratories in any advertising or sales promotion which would indicate or imply that the Environmental Research Laboratories approve, recommend, or endorse any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this Environmental Research Laboratories publication.

CONTENTS

PREFACE

The grounding of the supertanker Amoco Cadiz near the coast of Brittany on March 16, 1978, resulted in the greatest single discharge of petroleum in maritime history, with tragic consequences for the people of France. Strong onshore winds and unusually high spring tides (quite unlike the conditions encountered in the Argo Merchant spill in late 1976) forced the 220,000 ton cargo of the vessel high on the beaches and well into estuaries and marshes along 210 kilometers of the Brittany coast. The effects of the spill, although not totally evaluated to date, were nonetheless devastating in a region heavily dependent on the quality of its coastline and nearshore waters for the maintenance of an active maritime economy and way of life.

Few coastal regions of the world are immune from incidents of this nature; lessons learned from the French experience must be immediately translated into effective national and international regulations governing the safe shipment of petroleum and other hazardous substances by sea. In addition, we must establish the means to deal more effectively with incidents of this magnitude when they do occur. The French experience, as regrettable as it was, will yield a wealth of information on the effectiveness of various means of containment and cleanup and improve the capability of scientists and engineers around the world to mitigate and assess the environmental consequences of such events in the future.

The United States was fortunate to have in place a team of Federal, state and academic scientists trained and equipped to respond on short notice to marine pollutant incidents of this nature. Through the cooperation of the French government, members of the team were able to work closely with their French counterparts to assist in mitigating the effects of the spill, assess the extent of environmental damage, and compile information vital to future United States efforts in this area.

This report is a preliminary U.S. contribution to the study of the Amoco Cadiz disaster. A longer-term, international effort is clearly warranted to explore the long-range environmental consequences of the incident, as well as to understand the nature and effectiveness of natural recovery processes. Certainly the United States will continue to support this endeavor.

Richard A. Frank

Richard A. Frank, Administrator
National Oceanic and Atmospheric Administration

ACKNOWLEDGMENTS

The United States' scientific team is deeply indebted to Dr. Lucien Laubier, Director of the Centre Oceanologique de Bretagne of the Centre National pour l'Exploration des Oceans (COB/CNEXO), for the opportunity to participate with our French counterparts in the study of the Amoco Cadiz incident. Through Dr. Laubier's kind assistance and that of Dr. Allen, Dr. Cavanie, Dr. Conan, M. de Clarens, Dr. Marchand, Dr. d'Ozouville and other staff members and scientists at COB/CNEXO, scientific advice and laboratory facilities and equipment critical to the United States effort were provided.

We are also especially appreciative of the keen insights and valuable assistance offered by Dr. Cabioch, M. Leglise, D. J. Vasserot, and the staff of the Station Biologique Roscoff in aiding our work on the north coast. Considering the devastation of this most diverse and important biological habitat, it is with mixed emotions that we acknowledge the major contributions the station is now making to understanding the consequences of world oil pollution.

We would like to acknowledge the assistance and fruitful discussions provided by Drs. Glemarec and Chasse of the Université de Bretagne Occidental, Col. Ph. Milon and P. Penicand of the Ligue Francaise par la Protection des Oiseaux, and the staff of the Societé pour l'Etude et la Protection de la Nature en Bretagne.

Our work was aided in great measure by James Brown at the Department of State and William Salmon, Harvey Ferguson, and Quincy Lumsden at the U.S. Embassy in Paris. Necessary diplomatic clearances as well as very practical on-scene assistance were provided in an expeditious manner, under circumstances that were often difficult and sensitive.

We would also acknowledge the essential support provided by our interpreters Catherine Cadon, Brigette de Clarens, Tina Loughlin, Sylvia Walensky, and J. Rubino, without whose assistance communications would have been impossible at times and difficult at best.

Funding in support of this effort was provided by the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, and the Bureau of Land Management.

1. EXECUTIVE SUMMARY

This document provides a preliminary account of the United States scientific efforts in response to the Amoco Cadiz oil spill during the period March 19 to May 15, 1978. The document expands on and updates material reported by the National Oceanic and Atmospheric Administration in April 1978 in the document entitled The Amoco Cadiz Oil Spill: A First Report of the SOR Team Activities. It should be emphasized that all material reported herein is indeed preliminary; final assessment of full impact of the incident will require the integration and interpretation of data taken by scientists from several nations. From our knowledge of previous spills, we anticipate that final assessment of the full extent of the impact may require a period of several years.

At approximately 11:30 p.m. on Thursday, March 16, 1978, the supertanker Amoco Cadiz went aground on a rock outcropping 1.5 km offshore of Portsall on the northwest coast of France (see Plates 1-1 through 1-7). The vessel contained a cargo of 216,000 tons of crude oil and 4,000 tons of bunker fuel. At 6:00 a.m. on Friday, March 17, the vessel broke just forward of the wheelhouse and thus started the worst oil spill in maritime history. During the course of the next 15 days, the bunker fuel and contents of all 13 loaded cargo tanks, which contained two varieties of light mideastern crude oil, were released into the ocean. The oil quickly became a water-in-oil emulsion (mousse) of at least 50% water, and heavily impacted nearly 140 km of the Brittany coast from Portsall to Ile de Bréhat. At one time or another oil contamination was observed along 393 km of coastline and at least 60 km offshore (Fig. 1-1). Impacted areas included recreational beaches, mariculture impoundments, and a substantial marine fishery industry.

On March 18, Dr. Wilmot N. Hess, Director of the Environmental Research Laboratories (ERL) of the National Oceanic and Atmospheric Administration (NOAA), contacted Dr. Lucien Laubier, Director of the Centre Oceanologique de Bretagne (COB) of the Centre National pour l'Exploration des Oceans (CNEXO), the French national oceanographic organization. Dr. Hess and Dr. Laubier arranged for participation by United States scientists in a joint Franco-American investigation of physical and chemical manifestations of the spill. On March 24, the agreement was expanded to include cooperative biological investigations through contacts initiated by Dr. Eric Schneider, Director of the Environmental Protection Agency's Environmental Research Laboratory in Narragansett, Rhode Island.

Since the Argo Merchant oil spill in December 1976, EPA and NOAA have collaborated in development of an interagency oil spill response team, encompassing a variety of scientific disciplines. In the United States this team has three functions:

(1) To provide authorities responsible for cleanup with highly-qualified scientific assistance in mitigating the environmental and socio-economic impacts of spills of oil and other hazardous substances.

(2) To provide scientific assistance in assessing the damage resulting from such spills.

(3) To maximize the research advantage offered by the spill situation, especially with respect to improving future response capabilities.

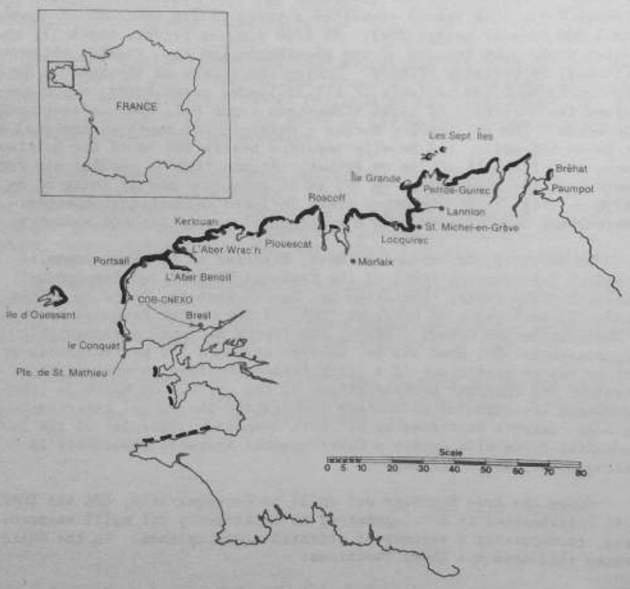


Figure 1-1. Coast of Brittany, showing locations of spilled oil.

NOAA team members initially arrived on-scene on Sunday, March 19. Initial photographic over-flights and active beach sampling began on Tuesday, March 21, followed by initial chemical sampling by vessel on Friday, March 24. The team was supplemented with EPA biological observers on Sunday, March 26. Routine sampling has continued by all segments of the team until the present time.

Throughout the period of investigation, active interaction and coordination with the French scientific community have taken place under the auspices of COB/CNEXO. All sampling has been coordinated with programs organized by CNEXO and other institutions in France, making possible a more thorough evaluation of the effects of the incident than would otherwise have been possible.

During the course of the investigation, seven observational objectives were established by the U.S. team:

(1) Aerial photographic mapping and ground surveys of impacted beaches.

(2) Statistical mapping of the distribution of oil on the water surface using vertical photography.

(3) Surveys of the concentrations of oil in subsurface water.

(4) Evaluation of the effect of weathering on the composition of surface oil as a function of time/distance from the wreck site.

(5) Evaluation of the long-term effects of weathering on the composition of oil in sediments from tidal flats and beaches.

(6) Evaluation of the biological consequences of the spill.

(7) Observation and assessment of cleanup techniques.

Given the limitations of our analytical efforts to date, we believe the following preliminary conclusions can be drawn regarding the nature, fate, and effects of the oil spilled from the Amoco Cadiz:

(1) According to our best estimate, 64,000 tons of the Amoco Cadiz oil came ashore along 72 km of the shoreline of Brittany during the first two and one-half weeks of the spill. A prevailing westerly wind pushed the oil against west-facing headlands and into shoreline embayments as it moved east. Additional wind-induced forcing is hypothesized to have taken place through a sea surface setup along the coast and subsequent development of a significant alongshore current. A wind reversal in early April moved the oil in the opposite direction, contaminating previously untouched areas and transporting the oil as far southwest as Pointe du Raz (southwest of Brest). At the end of April,

the total volume of oil onshore was reduced to 10,000 tons, but by that time 320 km of shoreline had been contaminated.

(2) Coastal processes and geomorphology played a major role in the dispersal and accumulation of the oil once it came onshore. For example, oil accumulated at the heads of crenulate bays and on tombolos (sand spits formed in the lee of offshore islands). Local sinks, such as scour pits around boulders, bar troughs (runnels), marsh pools, and joints and crevasses in rocks, tended to trap oil. The grounded mousse was either eroded away, or buried (up to 70 cm) under new sediment deposits, in response to the vagaries of the beach cycle.

(3) During the initial oiling, the first week after the grounding, oil definitely lifted off with the incoming tide, and was redeposited on the ebb. However, by late April oil/sediment binding was pronounced and considerable sinking was evident. A significant percentage of the oil spilled by the Amoco Cadiz is now hypothesized to have sunk to the bottom and thereafter been subjected to bottom transport processes.

(4) The distribution of oil in water in the Aber Wrac'h estuary was uniform vertically, indicating that the benthos was exposed to oil. Six weeks after the grounding, this estuary still contained elevated concentrations of oil in water, particularly at the upper end.

(5) Offshore, high concentrations of oil in water were observed under patches of mousse or slick, but, interestingly, near-bottom water usually contained even greater quantities of oil.

(6) Chemical analysis of weathered oil samples revealed notable losses of lower molecular weight components, decreases in peak heights of n-alkanes relative to isoprenoids, reductions in resolved vs. unresolved material in aliphatic and aromatic fractions, and increases in oxygenated material. Mass spectrometric data indicate the presence of photo-oxidation products of dibenzothiophene and its alkyl homologs. There was no mass spectral evidence for photo-oxidation products of the naphthalenes and phenanthrenes.

(7) Adverse biological effects of the spill were observed along the northwest coast of Brittany, ranging from Portsall to Perros-Guirec --a distance of about 150 km of coastline plus numerous rocky outcroppings and islands. Biological communities in these habitats were subjected to varying degrees of stress depending upon type of habitat, distance from the spill, and location relative to the configuration of the coastline.

(8) Intertidal communities on coastlines facing in a westerly direction, as well as the Aber Benoit estuary and Rulosquet marsh near Ile Grande, were severely impacted. These effects were maximized by spring tides which occurred just after the wreck. Massive mortalities of some intertidal animals occurred near St. Efflam and at Rulosquet

marsh over a relatively short time span (a few days), whereas mortalities of other populations were observed to occur more gradually (over several weeks). Populations of intertidal crabs, nereid worms, bivalve molluscs, and limpets were much more acutely affected by the spill than were deposit-feeders (e.g. Arenicola). For epifauna, mortality appeared to be related to physical coating by the oil; the dissolved fraction that penetrated into the interstitial water was probably the primary factor contributing to mortalities of infauna. Acute effects were not observed on attached macroalgae although some evidence was obtained in an independent study that indicates that the fertilization process of exposed plants may be impaired, and that growth of Laminaria may be retarded.

(9) The oil spill occurred at a time when many species of marine birds were in the process of migration from wintering to nesting grounds. More than 3,200 dead birds were recovered, representing more than 30 species. About 85% of these deaths, however, were among four species (shag cormorant, guillemot, razorbill, and puffin), the last three of which are considered rare or threatened in France. More chronic impacts on marine birds may result from feeding on contaminated prey. Seagulls were observed feeding on freshly killed intertidal organisms all along the impacted coastline.

(10) Mariculture operations for oysters were severely affected in the Aber Benoit and Aber Wrac'h estuaries and the Bay of Morlaix. Large numbers of oysters were either killed or contaminated by the spill. The holding pens of the commercial lobster operation at Roscoff were heavily oiled and probably will be out of operation for a year. The main scallop fishery in Brittany is located east of the impacted area, and adverse effects may be minimal.

(11) The transport of oil or its volatile fractions to terrestrial communities may have been substantial. In late March gale force winds and spring tides combined to deposit oil above the high tide mark. More importantly, some of the airborne fractions of the petroleum can adhere to plants and be transported to man via farm crops and livestock.

As indicated earlier, U.S. scientific response efforts were conducted for the purpose of meeting three objectives: 1) support to operational forces in mitigating impact, 2) assessment of damage, and 3) research for the purpose of improving the effectiveness of future responses.

In connection with objective 1, U.S. scientists provided assistance in suggesting alternative measures for dealing with oil contaminated beaches. Assistance in tracking the extent of oil contamination was provided to French authorities on a near-daily basis through frequent photographic overflights.

Most of the U.S. scientific activity will contribute to the final assessment of environmental damage in connection with the objective 2 above. U.S. biological observations, when merged with French data on pre-spill conditions, will contribute directly to the assessment of impact. Chemical analyses, coupled with information on the toxicity of crude oil and the expected distribution of biota at the time of the spill, will provide additional evidence of impact in the absence of direct biological observations in the field.

Regarding objective 3, major contributions to future U.S. response efforts are anticipated from observations of the clean-up strategies employed by the French and from after-the-fact assessment of each technique and the corresponding long-term impact on the environment. Data collected will also provide new insights concerning oil movement in the marine environment such as the stranding or beaching of oil, sheltering of areas in the lee of headlands, role of longshore drift in oil transport and the effect of tidal pumping. These new conceptual understandings can be expected to contribute to the next generation of oil spill forecasting models and hydrocarbon impact assessment studies.

2. INVESTIGATIONS OF PHYSICAL PROCESSES

J. A. Galt*

2.1 Introduction

The physical processes that affect the behavior of oil in the marine environment can be divided into two classes. The first class includes those processes that control the movement and mixing of ocean waters independent of the possibility of an added pollutant. These processes are the normal subject of study for physical oceanographers and represent a major research field in their own right. Normally we assume that these processes simply move the oil around and that in a Lagrangian frame of reference they define the position of the water parcels in which the oil (or hydrocarbon) floats. The second class of processes includes those that affect the oil and its distribution as it floats in the water. These processes clearly will depend on the physical and chemical characteristics of the oil as well as the environmental conditions. Oil/wave/wind interactions, mousse formation, and aglomeration with sediment particles are all contained in this second class of processes.

To develop an observation program and research effort that will offer tactical support during a spill situation and lead to a systematic improvement in our ability to forecast oil movement during future events we must consider all of these processes in some detail. In particular for coastal regions and expected oil types we must identify investigative and descriptive techniques that have proved useful, specify to what accuracy data fields must be known, and finally identify major gaps in our understanding of the processes that will require additional research.

When considering the first class of processes we may ignore the presence of oil and concentrate on the movement of the water and a passive tracer. The distribution of such a tracer will be described by the mass balance or distribution of variables equation (Sverdrup et al., 1942). This equation simply relates the local change in concentration to the divergence of the advective flux and diffusive spreading:

$$\frac{\partial c}{\partial t} = \nabla(c\bar{u}) + (k\nabla c)$$

*Pacific Marine Environmental Laboratory, NOAA, Seattle, Wash.

In an attempt to interpret this equation in an oceanographic context an immediate problem occurs with respect to the resolution of the velocity field specified in the advection term. In particular, any time dependent or unsteady components of the flow that are not included in the description of the currents contribute to the diffusive spreading term. Following the original development of Reynolds, effective diffusion coefficients can be defined which are typically orders of magnitude larger than those associated with molecular processes.

Conceptually, once we have determined how the water is moving we can treat the remainder of the trajectory problem by describing how the oil moves relative to the water. These relative motions will depend on the oil and its physical properties. These properties in turn will be governed by the complex chemical makeup that is typical of hydrocarbons. We can expect that such bulk properties as density and viscosity will certainly be significant. In addition there is considerable evidence suggesting that the oil's behavior is strongly influenced by processes that act across the oil/water and oil/atmosphere interfaces. Although these are poorly understood, a few examples can be noted.

Evaporation and fractionation during spreading will alter the composition of the upper surface of the oil, giving the exposed layer a set of characteristics different from those of the bulk of the oil. The result is the formation of a surface crust that can significantly alter the behavior of the oil slick as a whole.

For centuries seafarers have used oil floated on the sea to suppress wave action. The phrase to "put oil on troubled waters" has become part of common speech. Standard navigation texts have comments on the relative effectiveness of animal and vegetable oil vs. crude oil or gasoline (Bowditch, 1966). Despite this long observational history, the dynamics of the wave/oil slick interaction are poorly understood. It is just these details that are of particular significance to the oil transport and environmental impact problems. It is observed that short gravity waves and capillary waves are quickly damped out when entering an oil slick. The wave momentum must be transferred to the oil slick or a boundary layer just beneath it, or possibly both the slick and a boundary layer. The consequences of this process are at least twofold. First, the momentum exchange acts to propel the oil slick through the water, thus making it move faster than the surface drift in the direction of the dominant waves (downwind). In addition, since the shorter gravity waves and capillary waves have some components coming from all directions there will be an additional momentum transfer acting as a compressional force on the oil slick. This effect acts to counter the natural spreading of an oil slick and tends to reinforce surface tension effects. It can be seen that two major components needed in trajectory predictions appear to be closely tied to this wave/oil momentum transfer process: 1) differential oil water movement and 2) final expected spreading, pancake formation, etc.

Hydrocarbons once released in the marine environment cannot be treated as conservative quantities. As times goes on they are both modified in form and removed from the surface by a number of processes including evaporation, emulsification, sediment interactions, and biological degradation.

Some hydrocarbons will evaporate from a surface slick, resulting in significant losses of mass to the atmosphere. This process is not at all uniform and depends on a number of characteristics of the oil. Obviously the lighter molecular fractions of the oil tend to evaporate more rapidly than the heavier ones. This process modifies the bulk properties of the slick in such a way that certain feedback mechanisms become important. The heavy residuals left at the surface of the slick can form a crust or skin that inhibits further evaporation until mechanical processes, such as wave action, break or perturb the surface. Another important secondary effect associated with evaporation is the fractionation of the oil, which leaves the heavier component behind. In some cases the heavier fractions may be dense enough to sink. There have been examples where patches have sunk in relatively large chunks, and recent studies (Mattson, 1978) suggest that small flakes (which were presumably originally in suspension in the lighter oil fraction - USNS Potomac spill) can sink as a residual after evaporation. Observational data show very large variations in the loss of mass of oil due to evaporation from spill to spill. Although the accuracy of the observations can certainly be questioned, the range of losses appeared to be from practically nil in the Argo spill (#6 oil) to over 50% in the Ecofisk spill (light crude oil).

A second weather process is associated with emulsification. It occurs in two ways, leading to quite different results. Oil-in-water emulsifications can form where small oil droplets go into suspension in water. In such a case the oil no longer behaves as a surface slick, but moves with the water, mixing throughout the upper layer somewhat like plankton. Sustained weather effects in this form are not known, but oil-in-water emulsions appear to get rid of the oil slick as a surface contaminant, so emulsification agents are often considered part of a cleanup strategy. A second, common type of emulsification is one in which the mixture contains up to 80% water. Such a water-in-oil emulsification, often called mousse, appears to resist certain types of continued weather and takes on physical properties quite different from those of surface oil. The development of algorithms to predict mousse formation is of major importance for predicting overall oil impact.

A third type of weathering process affecting oil slicks is related to oil interacting with suspended sediments in the water column. In at least some cases, oil droplets appear to adhere to sediment particles. This is not a universal effect, and probably depends on complex geochemical interactions as well as oil characteristics. For example, in the Santa Barbara blowout, sediment from the Ventura river sank large quantities of oil whereas large amounts of oil from the Argo spill did not appear to end up in the sediments. In other cases (the Arrow, the West Falmouth, and the Metula spills) it appears that mechanical mixing was actually responsible for oil being driven into the sediments where the weathering processes and residence times were entirely different from those of oil in the water column.

A fourth weather process is related to biological utilization of the hydrocarbons as an energy source. This tends to be a slower process than the ones mentioned above and consequently is of secondary importance at least during the initial stages of a spill. For the long term fate of spilled hydrocarbons, biological breakdown is still likely to be significant, but this is typically beyond the period when trajectory tracking techniques can contribute to a meaningful estimate of the hydrocarbon mass balance.

2.2 Physical Processes Studies

Beginning our specific discussion of physical processes affecting the movement and spreading of oil spilled from the Amoco Cadiz it is necessary to consider the basic oceanographic background. This means looking into the dominant physical mechanisms controlling the regional surface flow. Before doing this, however, we will consider the purely observational data that describe the form of the floating oil. During the Amoco Cadiz study the SOR Team took a large number of photographs of floating oil and it is useful to try and categorize them.

2.2.1 Dominant Forms of Floating Hydrocarbons

The most common form of heavy oil concentration was a pool of floating mousse (Plate 2-1). This was generally brown to reddish-brown in color. Thicknesses were estimated to be typically about 1 mm although along shorelines thicknesses of as much as 25 cm were observed. A number of near-shore samples were collected and appeared to be very stable water-in-oil emulsions with 50 to 70 percent water contents. The time required for an oil to form a water-in-oil emulsion or mousse depends on the type of oil and the mixing energy available. For the Amoco Cadiz spill the formation appeared to take place very quickly. During overflights on March 21 and 22 the oil leaking from the ship appeared to change color from black to a brown characteristic of mousse in less than a ship length. A sample was collected on March 26. This sample was obtained at the point where the oil was upwelling to the surface mid-ship at the vessel. It proved to be a well developed mousse, indicating that the sea-water/oil combination in the ship's tank was forming an emulsion even before it left the ship.

A second common form of the oil was a sheen. Plate 2-2 shows a mousse and sheen combination under high wind conditions. The sheen is quite thin showing rainbow colors to a light gray appearence. This suggests thickness of about 10 microns. Such sheens were often seen in

conjunction with mousse concentrations but also appeared by themselves. Under moderate and strong wind conditions sheens always appeared to form windrows as would be expected from Langmuir cells. Previous SOR team observation on the Hawaiian Patriot spill suggest that windrow distribution of both sheen and mousse is likely to occur under strong wind conditions at extended distances. More recent SOR team studies of the Potomac spill (Mattson, 1978) indicate that sheen formation actually represents a fractionation in the oil with lighter, lower surface-tension components going into the sheen. Lighter hydrocarbon fractions are also more rapidly weathered by evaporation and dissolution so, as the surface oil ages, sheens would be less likely and the remaining oil might be expected to have a different molecular composition.

A third form of the Amoco's oil was a light brown foam (Plate 2-4). The chemical composition and origin of this form are unknown. It usually appeared in the highly energetic surf zone and was originally hypothesized to be a violently mixed mousse, a frappe, or perhaps mousse shake. It is also possible that this could be a surface product left as a residual after the use of dispersants. For whatever the reasons, the froth form apparently did not occur except in the surf zone and if it ever contributed to the development of more dense concentrations of hydrocarbons, that was not documented.

During the cruise of Le Suroit in early April it was possible to observe mousse concentrations at sea that had weathered for several weeks. Plate 2-3 shows a close-up photograph of weathered mousse that had congealed into smaller globs. It appears that this form does not have the extensive sheen that was seen earlier in the spill. It should also be noted that nothing is now known about the chemical composition of mousse in this form, or about its appropriate physical or environmental descriptors, its toxicity, effective viscosity, etc.

So far we have considered the empirically observed form of the oil in its most general catagories. We must now consider specific processes and dynamic forces affecting the spilled oil distribution.

2.2.2 Tidal Processes

A first glance at the Brittany coast of France suggests tidal action as a dominant process. A spring tidal range of 7 m certainly controls the near-shore currents. Within the estuaries and coastal zone the ebb and flow will contribute to beaching processes. On a slightly larger scale the tidal currents may or may not represent a significant process in the distribution of hydrocarbons. The answer to this question will depend on 1) the net flow over a tidal cycle; 2) the presence of convergences or divergences in the surface tidal currents; and 3) the possibility of correlations between the tidal currents and sources and sinks for the oil.

To the extent that tidal currents are linear the net flow over a tidal cycle will be zero and, although any water parcel will go through a displacement of perhaps several kilometers, the longer term drift will not accumulate. We know however that the tides are not strictly linear and that frictional effects, field acceleration terms, and shallow water effects all contribute to net displacements. Analytical estimates of these effects are difficult to obtain, but numerical modeling techniques can be used to indicate typical values (Nihoul, 1975). In his book Nihoul discusses work by Ronday (1972) which considered the residual flow patterns for the North Sea. Ronday estimated a transport through the English Channel in January to be 0.24×10^6 m^3/sec. If approximately correct this value would imply, for a cross-sectional area typical of the Brittany region, net average flows of a few centimeters per second. The tidal currents along the channel are known to be affected by rotation so the average value is certainly low for the French Coast, but even if it were doubled to account for this asymmetry it would still be about 5 cm/sec or less. This value of ~1/10 knot does not appear to be significant in the context of the Amoco Cadiz spill.

The next aspect of the tidal flow that will be of interest in the oil spill problem is the horizontal convergences or divergences. Proudman (1953) described the tides in the English Channel as made up of co-oscillations with the Atlantic and North Sea. A more detailed and observationally base description is presented in Defant (1961). The relevant result of these independently driven co-oscillations is a series of convergence and divergence lines. Defant describes three different sets of these, with the westernmost one entering the Channel from the Atlantic and first appearing off the Brittany Coast.

These convergence and divergence lines are also presented in the tidal current tables for the channel (Service Hydrographique et Oceanographique De La Marine-Paris-No. 551). Figure 2-1 shows the progression of these through a tidal cycle. As they move across the region, the line of convergence will concentrate bands of floating pollutants and divergence lines will cause spreading. For patches of floating mousse this process can certainly be expected to cause periodic changes in the percent of surface concentration of oil. If the convergence line is sharply defined and the initial concentrations heavy we may actually expect patches to run together with a subsequent change in the thickness distribution. If horizontal motion were the only consideration these moving fronts would periodically concentrate and rarefy the patches of floating oil with perhaps little net effect. The consequences of these tidal convergences can be expected to have a quite different effect on oil fractions whose relative buoyancy is reduced. This might include thin sheens, oil in accommodated droplets, or oil in water emulsions such as would result from the use of dispersants. For all of these forms the vertical velocity associated with the tidal convergence will carry the hydrocarbons away from the surface. This vertical transport process that continually sweeps along the channel may represent a dominant mechanism for mixing. During each tidal cycle the oil that is

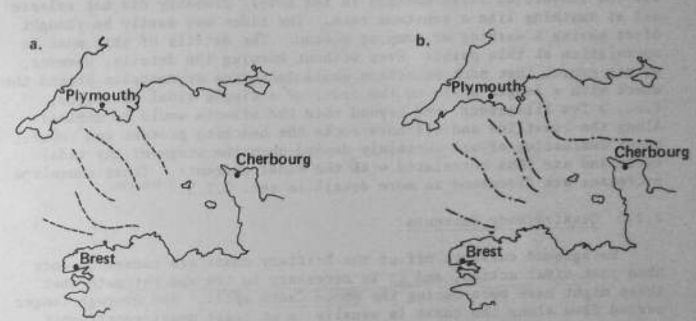


Figure 2.1 Hourly progression of tidal convergence line associated with (a) flood currents (eastward flowing off Brittany) and (b) ebb currents (westward flowing off Brittany). Successive position of line moves from west to east.

advected down can then mix horizontally and although the following tidal divergence will tend to replace some surface water from below it in no sense un-mixes the oil, and the overall net flux is downward. It may also be worth noting that these regular convergence patterns seem to be most prominent slightly offshore, which is where dispersants were regularly used during the Amoco Cadiz spill. This suggests that subsurface hydrocarbons may have been distributed through greater-than-expected depths. This would tend to enhance overall mixing, thus impacting larger portions of the marine environment, but with reduced concentrations.

The third tide-related process that could potentially affect hydrocarbon distributions depends on correlations between the tidal currents and any other transport or source/sink processes. The wind data for the Brittany Coast are being analyzed, but are not expected to be correlated, with the tides over any significant number of tidal cycles. The question of correlation of sources and sinks with the tidal flow is likely to require a bit more thought. The Amoco Cadiz, grounded as it was and subject to large changes in sea level, probably did not release oil at anything like a constant rate. The tides may easily be thought of as having a washing or pumping action. The details of this must be speculation at this point. Even without knowing the details, however, we can expect that such an action would introduce asymmetrics around the wreck with a length scale on the order of a single tidal excursion, i.e., a few kilometers, and beyond this the effects would be minimal. Along the coastline and offshore rocks the beaching process and subsequent refloating of oil certainly depend upon the stage of the tidal cycle and are thus correlated with the tidal currents. These shoreline processes are discussed in more detail in sec. 2.2.5.

2.2.3 Quasi-Steady Currents

Background currents off of the Brittany coast are caused by more then just tidal action, and it is necessary to try and estimate what these might have been during the Amoco Cadiz spill. The average longer period flow along the coast is usually in at least quasi-geostrophic balance, with both baroclinic and barotropic modes being present. The appropriate time and length scales for the set-up and adjustment of these currents is associated with the coastal upwelling problem. A number of studies of this process have taken place for many coastal regions. Of primary interest are the surface currents which are caused by the sea surface gradient normal to the coast. These gradients are caused by the Ekman transport onshore which in turn is related to the alongshore component of the wind. To determine characteristics of this flow we may consider modeling studies recently carried out by Hamilton and Rattray (1978). They show that alongshore wind stress of 1 dyne/cm^2 results in a current structure that builds up over a 5 to 10 day period with velocities in the first 10 to 20 kilometers offshore on the order of a knot and in the direction of the wind. The surface currents are seen to depend somewhat on the stratification, geometry, and mixing coefficients, but the qualitative results are not changed. During the first ten days of the Amoco Cadiz spill when the majority of the oil was discharged the dominant wind direction was from the west. This set up the necessary conditions for a coastal current to the east along the Brittany coast. Obviously the winds were not constant and the appropriate independent parameters are unknown but flows of about 1 knot are probably a reasonable estimate for this period.

2.2.4 Direct Wind Driven Oil Movement

As we have suggested the regional winds averaged over a few days will set up an alongshore current that should be a major factor in the advection of the oil. The wind will also contribute more directly to the movement of the floating oil. The wind/wave/oil momentum exchange, which is usually simply parameterized as a wind factor, will require a more detailed look at the wind field. Figure 2-2 presents stick diagrams representing the winds measured along the Brittany coast. These clearly show the dominance of winds from the west during the last part

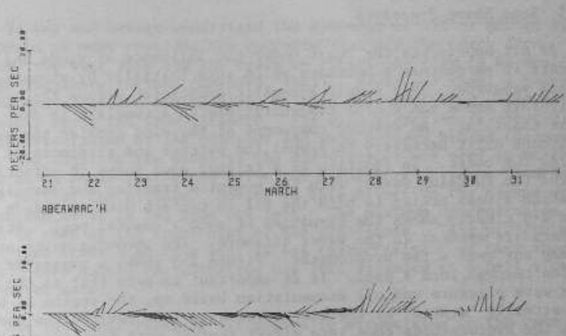


Figure 2.2 Stick diagram of wind observations for a number of locations along the Brittany coast.

of March. One conspicuous exception to this trend occurred on March 27-28 when strong winds developed with a northerly component.

By combination of the barotropic coastal current and the wind drift factors, initial trajectory estimates can be obtained. We must certainly expect that for most periods the hydrocarbons will move east and remain near the French coast. The wind event of March 27-28 would be an exception with oil moving offshore in a NNE direction. According to results of standard trajectory techniques the oil or mousse in the band along the coast could be expected to advance at speeds of about 1 knot with higher or lower velocities depending on the winds.

These admittedly first-order trajectory estimates point to two things. First is the obvious and easily observed fact that the Amoco Cadiz oil could be expected to impact the coast from the scene of the wreck spreading rapidly east. The second is that standard trajectory or forecasting techniques are not going to be particularly useful or informative for this spill. The most striking features of the Amoco spill were its massive size and its lee shore position. This means that very near shore transport and beaching processes will be significant and the opportunity to study them excellent. We now turn our attention to those near shore processes.

2.2.5 Near Shore Processes

As oil approaches the coast under the influence of winds and tidal currents it encounters a boundary which acts initially by stopping its forward progress. This simple kinematic constraint allows the relatively thin sheen and mousse concentrations to accumulate in deep pools at the coastline. An onshore component of the wind creates the waves and Stokes drift necessary to propel the patches and streamers of oil towards the coast. In addition as a thicker pool forms it effectively absorbs the incoming waves, with the momentum transfer and associated radiation stress acting to hold the oil in contact with the beach face. Plate 2-5 clearly shows the formation of such a coastal pool. Streamers of sheen are evident in the water offshore. The incoming waves are seen to damp out over a few wavelengths. Figure 2-3 shows a suggested cross section through such a pool. It is important to note that as the onshore wave pressure and oil accumulation build up, the region of beach face actually "wetted" by the oil increases. This defines the area over which the hydrocarbons come into direct contact with the sediments and will be the area where we can expect the most deposition of pollutants.

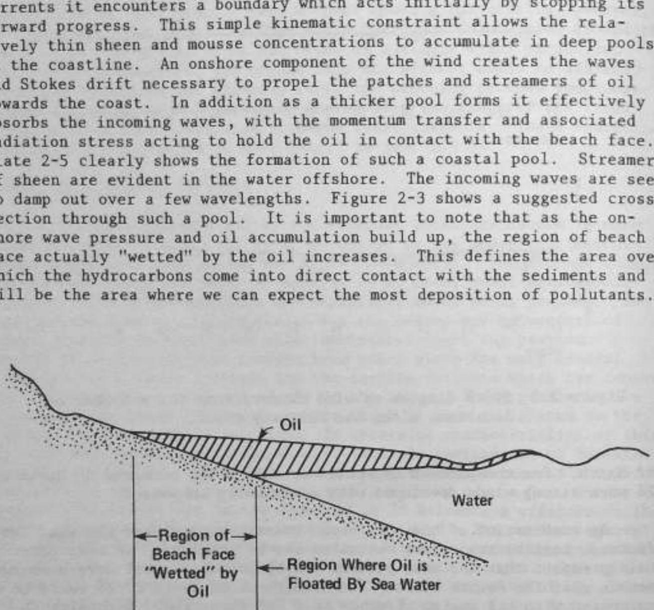


Figure 2.3 Suggested cross section through an oil pool held against the beach face by wind and wave stress.

The accumulation of mousse in pools along the shore is obviously a small-scale process and we can expect that the local geometry and beach face orientation will play an important role in determining where these occur. Plate 2-8 shows a small bay where an oil pool is being fed by offshore streamers. As the oil accumulates it simply fills up the available surface area of the bay and spills in a stream on down the coast. Small coves appear to act as ponds in the alongshore stream of oil. They are obviously holding areas for the oil that is pushed against and along the coast.

To try and better understand the movement of oil or mousse along the beach we must consider the currents just off the beach face. Between the surf zone and the beach we expect the flow to be dominated by the longshore current (Shepard, 1963). Plate 2-7 shows a heavy mousse concentration moving along in this nearshore band. The pool is obviously being fed from offshore. The wind direction is clearly seen by the orientation of the windrows and wake pattern behind the moored boat. In addition the waves in the mid-distance are seen to strike the beach at an angle that would drive the alongshore currents towards the lower part of the picture. Moving in this direction the mousse will accumulate as it is fed from the left. The maximum concentration alongshore is seen at the lower edge of the photograph. This picture was taken just after high tide and, as was characteristic of many observations, heavy mousse concentration was left stranded in a belt along the high-water mark.

The fact that floating oil naturally accumulates in the band dominated by alongshore drift leads to the conclusion that oil concentrations will tend to follow the same accumulation patterns that finer sediments do while undergoing beach drift (Kuenen, 1950). This analogy will prove useful along exposed beaches and we should expect tombolos to concentrate oil and rip currents to eject oil through the surf zone back offshore. Trying to extend these ideas into a low energy situation however is certainly not going to be correct since floating oil will act differently from either surface water or sediments, no matter how fine. To get a clearer idea of what to expect in these cases we may look at Plate 2-6. This picture shows mousse and sheen moving through a narrow opening between offshore rocks. A number of small-scale physical processes are seen. The wind direction is clearly indicated by the orientation of the windrows with upwind being toward the data panel. Wave patterns refracting through the opening are also clearly evident. Of particular interest is the separation of the floating oil in the lee of the rocks. The surface oil does not continue to "wet" the shoreline but is blown offshore and does not move with the water. In addition it continues to float and will not settle out the way sediments would to form a sand spit or bar. From Plates 2-6, 2-7, and 2-8 we can see that the small-scale orientation of the coast relative to the wind and waves will determine the patchiness expected in the alongshore distribution of oil. Alongshore drift will determine the movement of the oil along exposed beach sections, but headland and rock outcrops will protect lee areas, provided that a pocket is not formed that can fill up before spilling out back into the alongshore stream. It would be of considerable interest to understand the separation process taking place in Plate 2-6. Such processes will ultimately determine how much sheltering can be expected. It is also possible that protected lee areas offer a separation of direct wind and wave interactions with the oil and would make useful areas for observational studies.

In the previous discussion of transport mechanisms associated with tidal action, the occurrence of correlation between tidal currents and coastal sources and sinks was listed as a potentially significant transport process. We can now consider this in more detail.

Many examples of mousse being stranded by the receding tide were observed during the Amoco Cadiz study. In nearly all the cases the heaviest oil concentrations were deposited right along the high-water line. Plate 2-9 shows a striking example of this. Here we see a deep pool of mousse that was left by the tide and subsequently drained down the face of the beach. The mousse appears to be in a gravitational drainage pattern and obviously flowed more slowly then the actual tidal water receded. To the right and left of this pool stained sediments and oil accumulation in the rocks are also evidence of heavy exposure. Returning our attention to figure 2-3 it is possible to speculate on the factors contributing to the stranding of these heavy concentrations at the high water level. As the mousse forms a wedge along the shore because of onshore wave and wind stresses, the band where the beach face is actually in contact with the oil is moved up to the high-water mark. When the tide turns this oil tends to adhere to the sediments and be stranded, whereas below this point the water under the oil tends to float it free and relatively little is deposited. Subsequent tides may refloat the oil, bury it or add to it, depending on the onshore stresses and the stage in the spring neap cycle. In terms of transport processes it is significant to note that oil appears never to be deposited on a rising tide, but only during the ebb. The movement of oil alongshore then has full exposure to the flood tide currents and a somewhat reduced statistical exposure to the ebb current direction. Along the Brittany coast this contributes one more component to the eastward transport. This form of tidal transport is not limited to the coast line proper but also applies to offshore rocks. Plate 2-10 shows a rock outcrop during a rising tide. It definitely appears as a source re-introducing oil into the flooding tide. The significance of this mode of transport relative to other components must depend on the onshore stresses, the intertidal area, the general morphology of the coast, and the lee shore nature of the spill.

2.3 Summary and Conclusions

The Amoco Cadiz disaster presented a unique opportunity to study oil spills in the marine environment. The massive amounts of oil discharged, and its position close to a lee shore all made this a particularly interesting spill to study. A review of previous oil spill research and the conceptual state-of-the-art for oil spill trajectory modeling techniques indicates that in the past forecasting development has concentrated on open ocean spills. Contrasted to this, major environmental concern tends to be focused on the coast line. In addition improvements in trajectory analysis and impact assessment will require a better understanding of the processes controlling the thickness distribution of the oil. These conditions set the stage for planning specific studies to be carried out at the Amoco Cadiz spill.

The spilled oil appeared in a variety of forms. These could be described in terms of four classes: 1) mousse, 2) sheen, 3) light foam, and 4) weathered mousse as small globs.

Estimates were made of what was thought to be the dominant oceanographic or meteorological processes affecting the movement and spreading of the oil. Winds were strong during much of the spill event and contributed to the oil movement both directly and indirectly. Direct wind forcing was through wind/wave/oil interactions, and indirect forcing was hypothesized to take place through a sea surface set-up along the coast and subsequent development of an alongshore current system. Both components of the wind forcing tended to move the oil eastward in a coastal band during the March period of study. Tidal forcing was investigated and estimated to play an important role through convergences and divergences in the offshore area and through the beaching/tidal pumping sequence that took place along the coast.

Nearshore transport and beaching processes that lead to the stranding of oil were investigated. The orientation of the coastline and alongshore current system were seen to affect the oil distribution. The stranding of heavy oil concentrations appeared to occur only during ebbing tides and seemed conditional on the intertidal beach face (Fig. 2-3) coming in direct contact with the oil.

Photographic records from a number of transects were collected for an analysis of oil coverage, but these records have yet to be studied in detail.

The data collected at the Amoco Cadiz spill have given new insights into oil movement in the marine environment. These will prove useful in the development of conceptual algorithms to describe fundamental processes such as the stranding or beaching of oil, sheltering of areas in the lee of headlands, role of alongshore drift in oil transport, and the effects of tidal pumping. These new conceptual understandings can be expected to contribute to the next generation of oil spill forecasting models and hydrocarbon impact assessment studies.

2.4. References

Bowditch, N. (1966): American Practical Navigator, An Epitome of Navigation. Hydrographic Office Pub. No. 9., U.S. Naval Oceanographic Office.

Defant, A. (1961): Physical Oceanography, Vol. II, Macmillan, New York, N.Y.

Hamilton, P., and M. Rattray (1978): Numerical model of the depth dependent wind-driven upwelling circulation on the Continental Shelf (in revision for publication in J. Phys. Oceanogr.).

Kuenen, Ph. H. (1963): Marine Geology, Wiley, New York, N.Y.

Mattson, J. S. (1978): Personal communication.

Nihoul, Jacques C.J., Ed. (1975): Modeling of Marine Systems, Elsevier, Amsterdam, Oxford, N.Y.

Proudman, J. (1953): Dynamical oceanography, Methuen, Strand, England.

Ronday, F. C. (1972): Modele mathematique pour l'etude de la circulation residuelle dans la mer du Nord. Marine Science Branch, Manuscript Report Series, 27, Ottawa, Canada.

Shepard, F. P. (1963): Submarine Geology, second edition, Harper & Row, New York, N.Y.

Stolzenbach, K. D., O. S. Madsen, E. E. Adams, A. M. Polack, and C. K. Cooper (1977): A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks. Ralph M. Parsons Laboratory, Report No. 222, MIT, Cambridge, Mass.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming (1942): The Oceans, Their Physics, Chemistry and General Biology, Prentice-Hall, Englewood Cliffs, N.J.

3. CHEMICAL COMPOSITION OF SELECTED ENVIRONMENTAL AND PETROLEUM SAMPLES FROM THE AMOCO CADIZ OIL SPILL

John A. Calder,[1] James Lake,[2] and John Laseter[3]

3.1 Introduction

The analyses described in this document represent initial chemical investigations by the University of New Orleans' Center for Bio-Organic Studies (UNO-CBS), the U.S. Environmental Protection Agency, Environmental Research Laboratory, Narragansett (EPA-ERLN), and the National Oceanic and Atmospheric Administration's National Analytical Facility (NOAA-NAF), on the composition and fate of oil spilled along the Brittany coastline by the Amoco Cadiz. While many of the analyses are qualitative in nature, much quantitative information is presented. The information reported is useful in studying the nature and composition of the initial petroleum entering the environment and the transformations of this material as part of the weathering process.

Selected samples were collected at different locations along the Brittany coastline during the days and weeks immediately following the oil spill. Station locations are shown on the map of the Amoco Cadiz oil spill study area, Fig. 3-1. Sample locations and descriptions are presented in Table 3-1. Many samples were collected in areas that were heavily contaminated and had visible oil. These samples included weathered oil samples floating on the water surface, samples of the mousse (water-in-oil emulsion) and oily froth, soils, sediments, water column samples, and biota samples such as sea grass, polychaetes, and periwinkles from the tidal zone. Also a neat, medium Arabian crude oil was analyzed as a standard. There are approximately 120 samples discussed in the report. These were used for over 200 individual gas chromatographic analyses and approximately 20 gas chromatographic-mass spectrometric (GC-MS) analyses. Due to limited space only representative portions of these analyses are reported.

---

[1]NOAA/ERL, OCSEAP, Boulder, CO 80302
[2]U.S. EPA/ERL, Narragansett, RI 02882
[3]University of New Orleans' Center for Bio-Organic Studies, New Orleans, LA 70122

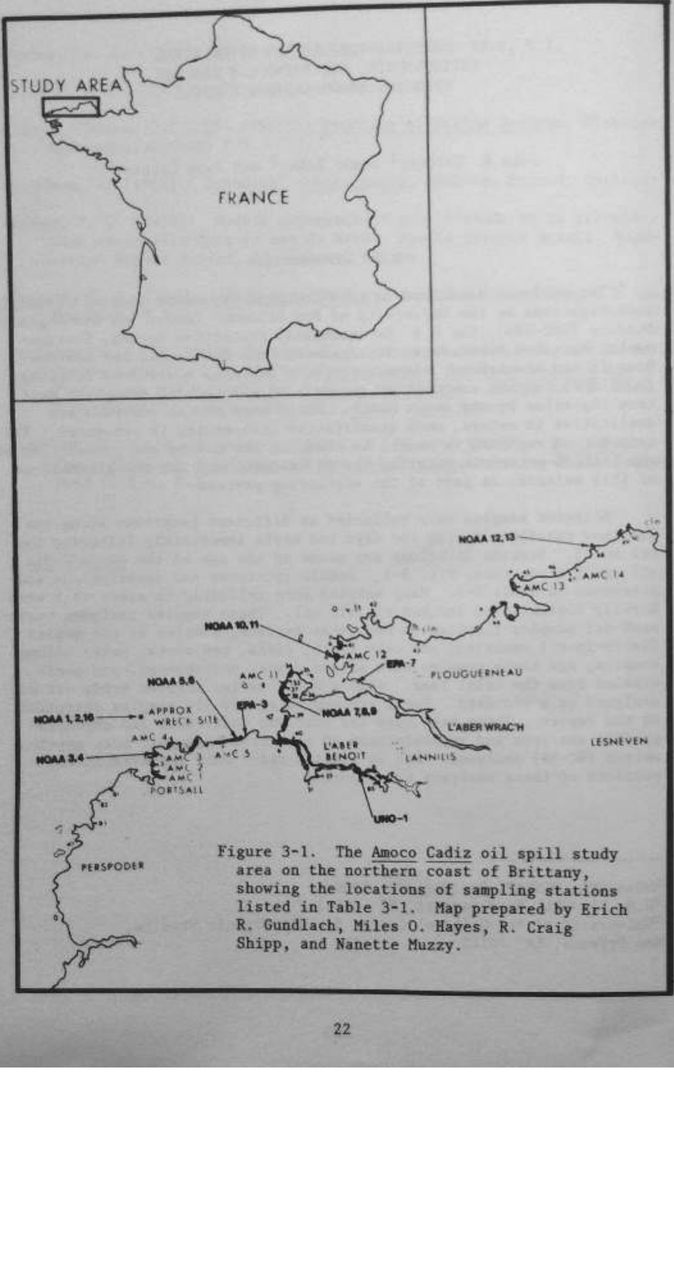


Figure 3-1. The Amoco Cadiz oil spill study area on the northern coast of Brittany, showing the locations of sampling stations listed in Table 3-1. Map prepared by Erich R. Gundlach, Miles O. Hayes, R. Craig Shipp, and Nanette Muzzy.

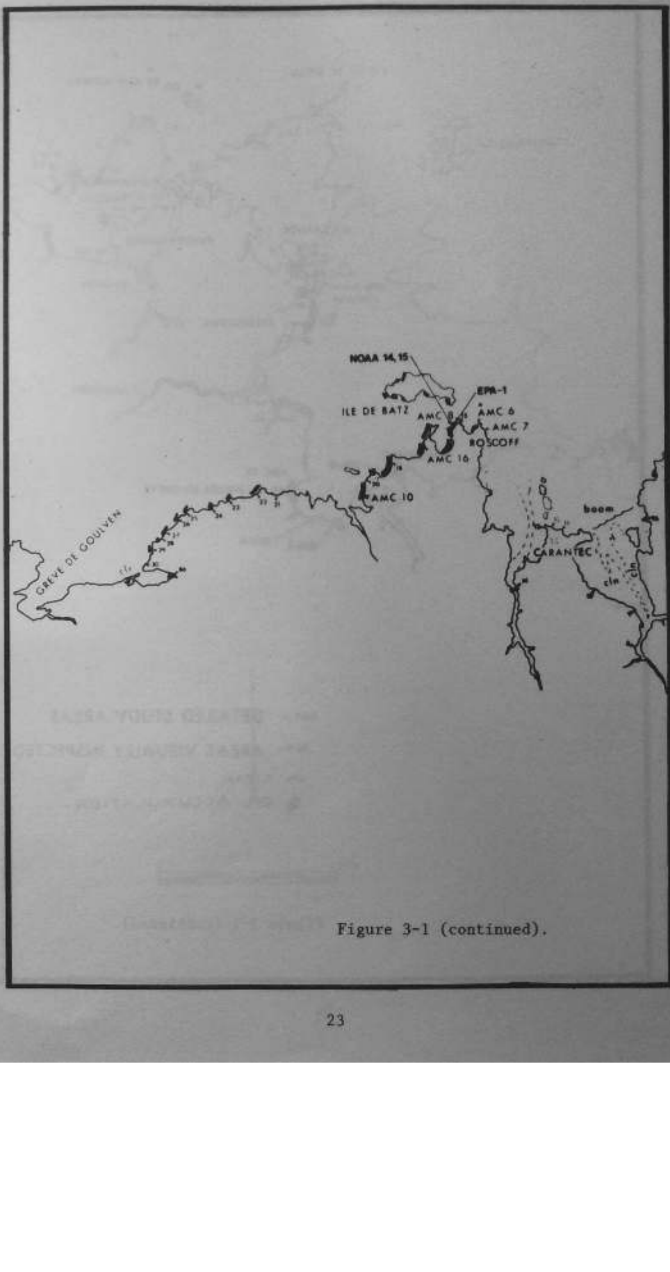


Figure 3-1 (continued).

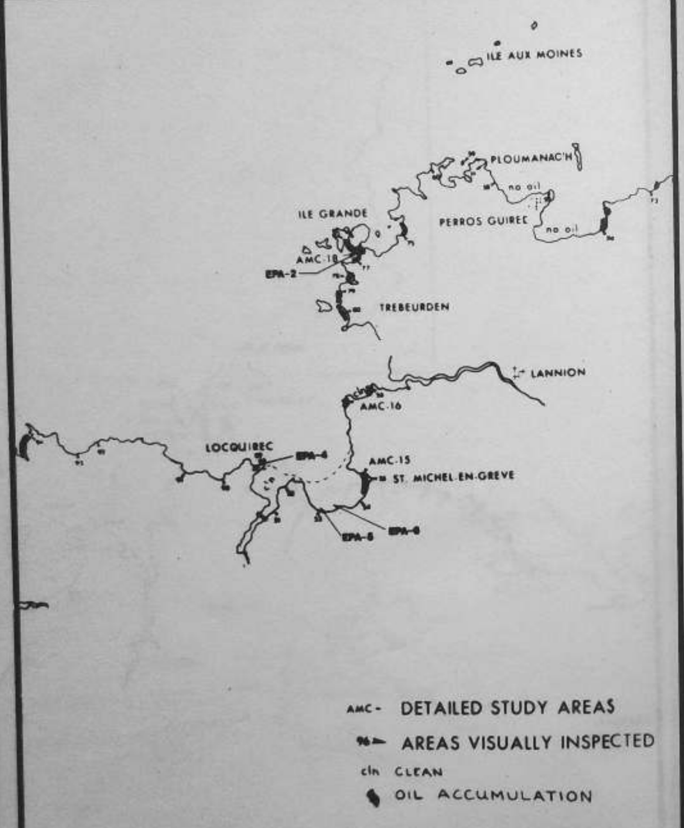


Figure 3-1 (continued).

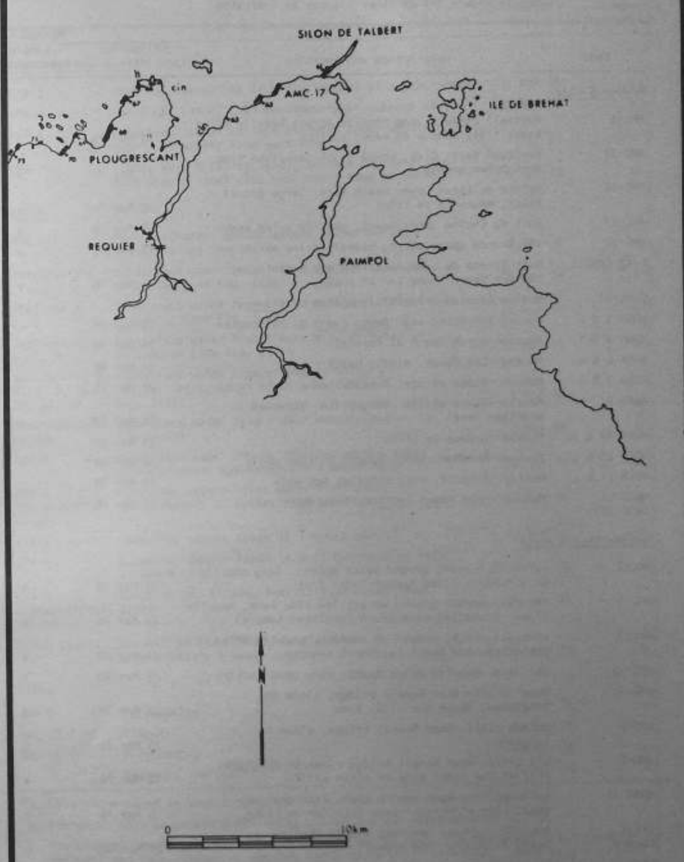


Figure 3-1 (continued).

Table 3-1. Location, description, collection date, and method of sample preservation of Amoco Cadiz oil spill samples analyzed. Locations are shown in Figure 3-1 or other figures as indicated.

Code	Description and location	Collection date	Method of sample preservation*
Mousse & oils			
AMC-1	Portsall center, long profile across heavily oiled tidal flat, mousse on water surface	31 Mar 78	a
AMC-14	Kerlouan Yacht Club, brown froth downslope from dark brown mousse	27 Mar 78	a
AMC-16	Pointe de Lekar upper beach face, large gravel beach, mousse 5 cm thick	28 Mar 78	a
AMC-17	Port la Chaine upper beach, heavily oiled beach	29 Mar 78	a
AMC-18	Ile Grande upper marsh, heavily oiled marsh	29 Mar 78	a
F-82 (UNO1)	Near Pointe de Landunvez from mid beach face, boulder beach, some tar on rocks	31 Mar 78	a
Control	Medium Arabian crude oil supplied by Aramco		-
NOAA 1 & 2	Mousse collected near Amoco Cadiz by helicopter	23 Mar 78	-
NOAA 3 & 4	Mousse--north beach at Portsall	24 Mar 78	-
NOAA 5 & 6	Mousse--Les Dunes, middle beach	24 Mar 78	-
NOAA 7 & 8	Mousse--Dunes at Ste. Marguerite	24 Mar 78	-
NOAA 9	Mousse--Dunes at Ste. Marguerite, stranded at mid-tide level	24 Mar 78	-
NOAA 10 & 11	Mousse--Grèves de Lilia	24 Mar 78	-
NOAA 12 & 13	Mousse--Meneham, thick mousse in tide pools	24 Mar 78	-
NOAA 14 & 15	Mousse--Roscoff, very thick at sea wall	24 Mar 78	-
NOAA 16 (AMC-30)	Mousse--near Amoco Cadiz by helicopter	27 Mar 78	-
Sediments and soils			
AMC-1	Portsall center, ground water across, long profile of a heavily oiled harbor-tidal flat	31 Mar 78	a
AMC-3	Portsall north, ground water, low tide berm, heavily oiled, protected sand beach (sediment sample)	31 Mar 78	a
AMC-3	Portsall north, mousse on surface, heavily oiled, protected sand beach (sediment sample)	31 Mar 78	a
AMC-12	St. Cava, heavily oiled beach, many dead cockles	27 Mar 78	a
UNO-2	Upper cliff--Aber Benoit bridge, close to Treglonou, above the tidal zone	31 Mar 78	a
UNO-2	Bottom cliff--Aber Benoit bridge, close to Treglonou	31 Mar 78	a
UNO-2	Oil cliff--Aber Benoit bridge close to Treglonou, soil at the tidal base of oiled cliff	31 Mar 78	a
NOAA 17	Sediment from Aber Wrac'h tidal flat near the small town of Perros--same location as EPA-7	6 Apr 78	-
EPA-1 (beach)	Roscoff--surface sediment (sand) obtained on beach 70 meters from seawall	27 Mar 78	b
EPA-1 (tidal flat)	Roscoff--surface sediment (sand) obtained on tidal flat 270 meters from seawall. Water depth was approximately 2 cm.	27 Mar 78	b
EPA-2	Ile Grande--surface sediment (clay and silt) obtained after mousse and oil had been scraped from the surface	30 Mar 78	b

Table 3-1. (continued)

Code	Description and location	Collection date	Method of sample preservation*
Sediments and soils (continued)			
EPA-3	(0-5 cm) (sand) Top five centimeters of a beach core	31 Mar 78	b
EPA-3	(5-10 cm) (sand) 5-10 centimeters of a beach core	31 Mar 78	b
EPA-4	Locquirec (sand) surface sediment taken approximately 30 meters from surf zone	2 Apr 78	b
EPA-7	L'Aber Wrac'h (silty sand), surface sediment from Aber Wrac'h tidal flat near small town of Perros	6 Apr 78	b
Water			
AMC-17	Port la Chaine, ground waters below top of heavily oiled beach	29 Mar 78	a
Stations 1-7	Subsurface water from l'Aber Wrac'h--total of 8 samples (see Fig. 3-24)	24 Mar 78	c
Stations A, B, C	Subsurface water from l'Aber Wrac'h--total of 7 samples (see Fig. 3-25)	25 Mar 78	c
Stations A, B, C, D	Subsurface water from l'Aber Wrac'h--total of 16 samples (see Fig. 3-26)	27 Mar 78	c
Stations 1, 3, 6, 7, 9, 16, 29, 37, 39	Subsurface water from offshore, Le Suroit cruise, Leg I, total of 26 samples (see Fig. 3-31)	30 Mar - 4 Apr 78	c
Stations 1-7, bridge	Subsurface water from l'Aber Wrac'h (see Fig. 3-27)	3 May 78	c
EPA-3	Subsurface water sample obtained at 0.5 meter depth in water approximately 1 meter deep	31 Mar 78	b
EPA-4 (Interstitial water)	Locquirec interstitial water from beach approximately 30 meters from surf zone	27 Apr 78	d
EPA-4 (surf)	Locquirec sample taken at 1 meter depth	27 Apr 78	d
EPA-4	Locquirec sample taken in pool surrounding rock on beach	6 Apr 78	b
EPA-5 (interstitial water)	Beach at St. Efflam, interstitial water from beach	27 Apr 78	d
EPA-5 (surf)	In surf at St. Efflam, sample taken at approximately 1 meter depth	27 Apr 78	d
Biota			
AMC-4	Periwinkles	29 Mar 78	a
AMC-17	Limpets	29 Mar 78	a
AMC-18	Polychaetes	29 Mar 78	a
	Seagrass, Portsall	31 Mar 78	a

*a. Chloroform added to sample--transported at room temperature.

b. Frozen as soon as possible following collection and maintained at -20°C.

c. Transferred immediately from Niskin bag sampler to hexane-washed green glass jug with Teflon-lined cap. Stored at ambient temperature until extracted. Aber Wrac'h samples extracted within 36 hours of collection. Offshore samples extracted on April 5, 1978.

d. Dichloromethane added to sample--transported at ambient temperature.

Prior to GC analysis, the total lipid extracts were simplified by liquid/solid chromatography. The silica gel (Davison, grade 923, 100-200 Mesh) was activated by overnight heating at 150°C. Aliphatic type compounds were eluted with three bed volumes of n-hexane. More polar compounds and aromatic type compounds were eluted with three bed volumes of 40% benzene in n-hexane. All other components were displaced with three bed volumes of methanol. The eluates from each fraction were reduced in volume on a rotary evaporator to approximately 5 ml and stored in a freezer until analyzed by GC and GC-MS. All Burdick and Jackson solvents were distilled in glass prior to use and their purity checked by GC. A splitless method of sample injection was employed for all gas chromatographic analyses, using Hewlett-Packard Model 5711 gas chromatographs equipped with FID detectors. These data were digitized into "area slice" data and transmitted to an HP 3354A central laboratory data system. UNO-CBS-developed software was used to integrate GC peak areas. Plots of the gas chromatograms, for display purposes, were generated from the digital raw "area slice" data on a Tektronix 4662 digital plotter by software developed at the Center. Similar plotting routines were employed to generate the three-dimensional displays.

The GC columns were 30 m by 0.3 mm ID and coated with either SE-52 or Carbowax 20M as the liquid phases. Extracts were injected, with the GC oven at 50°C and with a helium flow rate of 38 cm/sec. The oven was temperature-programmed at 4°C per minute to 240°C and held at 240°C until all peaks had eluted from the column. Back purging of the splitless injector system was activated 35 seconds after injection.

Mass spectral data were collected on a Varian MAT 311A high-resolution mass spectrometer. Separation conditions were the same as those described in the preceding paragraphs for GC. Effluents from the column were introduced directly into the ion source of the mass spectrometer via a heated glass capillary line without going through an enrichment device.

Mass spectra were scanned every 3.8 second at 70 eV and all data were stored on magnetic disc. The source temperature was 250°C. For routine sample runs, the resolution of the mass spectrometer was 1000 (m/M at 10% valley) and the mass range scanned was from 35 to 600 AMU. All mass spectral data were acquired in digital form by a Varian Spectrosystem 100 MS data system. Mass chromatrograms of specific ions were generated to aid in locating certain classes of compounds in the complex sample types analyzed in this program.

Photo-oxidation experiments were carried out in a two-phase system in which a given oil or mousse sample was dissolved in n-hexane on an aqueous saline solution (40 gm/L). Under conditions simulating environmental conditions, this system was irradiated with a visible source (Sylvania EHC 500 watt tungsten lamp covered by a uranium glass filter) which has a spectral output that approximates that of the solar spectrum. When necessary, oxygen was introduced through a fritted glass inlet. The products were isolated and fractioned in a fashion similar to that described previously.

The exact age of the weathered oil samples and the extent of exposure of oil to marine sediments, benthic organisms, and flora is not known because of the nature of the insult. Oil leaked from the grounded tanker over a period of approximately two weeks, making an exact assessment of the length of environmental exposure or degree of weathering of the oil a difficult task.

The analytical techniques used to examine these samples were primarily designed to establish quantitatively and qualitatively the extent of environmental contamination. Methods included high-resolution glass capillary gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS) analysis of up to three fractions from each sample isolated by liquid-solid chromatography. The three fractions were the saturated aliphatic type compounds, the aromatic type compounds, and the more polar organic compounds. Additionally, ultraviolet fluorescence (UV-fluorescence or UVF) was determined on aliquots of the hexane extracts from subsurface water samples collected in a heavily impacted estuary (l'Aber Wrac'h) and offshore oceanic waters. A towed underwater fluorometer was deployed in the estuary to provide real-time information on subsurface oil-in-water concentrations.

3.2 Methods

The following is a brief summary of the analytical methods employed by each participating laboratory. A survey of the data suggests that very similar results were obtained irrespective of the variations in extraction and analytical procedures employed. Compare gas chromatograms of the reference mousse (Figs. 3-4, 3-6, and 3-35) obtained by the participating laboratories. In all instances care was taken to insure that samples were not contaminated during collection, storage, or transport. Sample preservation methods are listed in Table 3-1.

3.2.1 UNO-CBS Procedures

Immediately prior to analysis of mousse samples, the entire content of the glass container was thoroughly homogenized and a small aliquot removed for fractionation. This aliquot was dissolved in 15% CH_2Cl_2 in n-hexane and any water was separated using a separatory funnel. The organic extract was reduced in volume on a rotary evaporator prior to column chromatography. In the case of biota, the samples were homogenized and then freeze-dried prior to extraction by refluxing overnight with 15% CH_2Cl_2 in n-hexane. The organic solvent was separated from the aqueous material after centrifugation using a separatory funnel, and then reduced in volume on a rotary evaporator prior to saponification. The saponification of biota lipids was accomplished using 0.5N NaOH or KOH in methanol/water reflux for five hours. The nonsaponifiable compounds were extracted three times with 60 ml of n-hexane. The extract was then reduced in volume prior to fractionation.

3.2.2 EPA-ERLN Procedures

Water samples were frozen or poisoned with 100 ml of dichloromethane after collection. After thawing (if necessary) samples were extracted three times with 100 ml of dichloromethane in a separatory funnel. Sample extracts were passed through a column of Na_2SO_4 and reduced in volume on a Kuderna-Danish evaporator fitted with a three-ball reflux column. Following solvent exchange to hexane, the volume was reduced under a stream of nitrogen. Extracts were analyzed intact or separated into aliphatic and aromatic fractions on a silica gel column.

A dry weight for the sediment samples was determined by drying an aliquot at 105-115°C for two hours. After addition of internal standards and additional water, the sediment was extracted under reflux in a solvent mixture of 70% 0.5 N KOH in absolute methanol. The sediment-solvent mixture was filtered through a glass fiber filter and the filtrate was extracted in a separatory funnel with petroleum ether. The combined extracts were evaporated to dryness on a rotary evaporator, redissolved in petroleum ether, and analyzed intact or separated into aliphatic and aromatic fractions on a silica gel column.

Extracts were analyzed by gas chromatography on a 30 m by .27 mm I.D. glass capillary column of SE-52 in a Hewlett-Packard 5840A gas chromatograph. A temperature program from 35°C to 290°C at a rate of 5°C/minute was used. The initial time was 4 minutes. The injection temperature was 290°; the flame ionization detector temperature was 280°. The splitless injection port was purged 1 minute after injection.

The GC-MS analyses were performed on a similar SE-52 column in a Shimadzu gas chromatograph connected to a Finnegan model 1015 mass spectrometer with a System Industries data system.

A weighed amount of the reference mousse (NOAA-16) was dissolved in hexane and used as an intact mousse standard. The separation of aliquots of this standard on a silica gel column yielded aliphatic and aromatic standards.

Quantification of chromatograms was accomplished by planimetering the areas of chromatograms and comparing the areas with areas obtained from known amounts of a mousse sample.

3.2.3 NOAA-NAF Procedures

Mousse samples were dissolved in n-hexane and a 5 ml aliquot was concentrated to ~ 0.5 ml. An internal standard was added and the resulting mixture was then directly analyzed by GC. In selected cases the mousse samples were centrifuged to break the emulsions. Because centrifugation at 2000 g for several hours was insufficient to break many of the mousses completely, high speed centrifugation was attempted. A

Beckman model L preparative ultracentrifuge (SW 50.1 rotor) was utilized for this test, employing polyalomar, 5 ml capacity tubes. The separation was performed at about 40,000 rpm (ca. 150,000 g), with refrigeration maintaining the unit at 18°C.

The separation achieved was a considerable improvement over the low-speed centrifugation, although complete separation was still not achieved in some cases. A sample which contained ca. 40% unseparated mousse at 2000 g still retained 3% as an emulsion even at 150,000 g. However, the time required to achieve this separation with the high-speed centrifuge was only 30 minutes, compared to several days for the low-speed procedure. The minimal amount of both handling and time minimizes losses of the more volatile compounds that are essential to the characterization of the oil from the mousse by gas chromatography (with respect to degree of weathering).

Most of the samples were separated into three layers: an oil layer, a water layer, and residual material that could not be further separated. The NOAA team also prepared n-hexane solutions of aliquots of the mousse and separated oil and analyzed them by GC, using a standard temperature program for petroleum hydrocarbons. Silica gel column chromatography was performed on selected mousse samples and oil samples and the three fractions generated were analyzed by GC and GC-MS.

All GC analyses were conducted with a Hewlett-Packard 5840A chromatograph equipped with glass capillary columns and FID detectors. An SE-54 liquid phase was employed on a 30m x 0.25mm WCOT column. A helium carrier at 24 psi with a 3 µl splitless injection was employed; the split valve was opened after 18 sec. The chromatographic oven program was held isothermal at 50°C for 5 min and then programmed at 4°/min. to 280°, then held at 280° for 30 min.

UV-fluorescence was determined on aliquots of the hexane extracts of subsurface water. The measurements were performed on a Perkin-Elmer MPF-44A dual-scanning fluorescence spectrophotometer. Mousse sample NOAA-16 was utilized as the best representative of cargo oil; other samples were compared to it as the standard. Every day that samples were processed, a new calibration curve was developed from serial dilutions of the reference mousse (NOAA-16) at an emission wavelength of ca. 360 nm. Emission was scanned from 275-500 nm, offset 25 nm from the excitation wavelength, and the major peak occurred at ~ 360 nm for the reference mousse solutions (see Fig. 3-2). In each sample, the concentration of fluorescent material, a total oil estimate, was calculated from its respective fluorescence, using the linear relationship of fluorescence vs. concentration of the reference mousse "standard." A correction factor was applied to account for the reference mousse containing only about 30% oil.

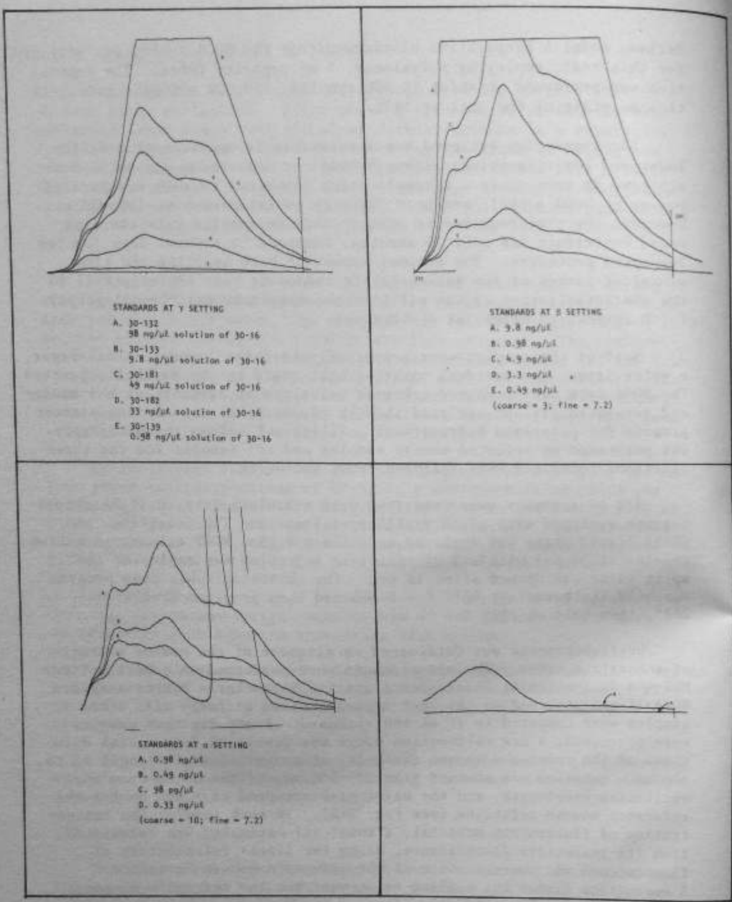


Figure 3-2. UV-fluorescence synchronous scans of serial dilutions of the reference mousse in hexane (figures showing γ, β, and α settings). Remaining figure shows hexane blank at most sensitive (β) setting. Major peak occurs at about 360 nm for the reference mousse.

3.3 Results

3.3.1 Mousse and Oil

Figures 3-3 and 3-4 show high-resolution chromatographic separations of the n-hexane and 40%-benzene-in-n-hexane fractions of the medium Arabian crude oil control sample (standard) and the NOAA-16 reference mousse, which represents a freshly formed mousse collected at the spill site. The n-hexane fractions of both samples showed similar normal, isoprenoid, branched, and cyclic hydrocarbon patterns from approximately C_{10} to C_{30} range. The normal hydrocarbons in the highest concentration generally occurred in the C_{16} to C_{18} range. Figure 3-4 illustrates the mass spectrometric identifications of the normal alkanes in the reference mousse sample, whereas Fig. 3-5 illustrates the identified aromatic components in the 40%-benzene-in-n-hexane fraction of a mousse sample collected at Ile Grande. The aromatic compounds numbered in Fig. 3-5 are identified in Table 3-2. This fraction was low in unsubstituted species, showing only a modest quantity of phenanthrene and dibenzothiophene. Notable was the inability to detect the four-ring and larger polycyclic aromatic hydrocarbons and their alkylated homologs. The GC profiles of the control and reference mousse samples collected adjacent to the Amoco Cadiz are very similar in the distribution of aromatics above the alkylated naphthalenes. There has apparently been a loss of the alkyl benzenes and related volatile aromatics in the mousse samples as compared to the control. It must be pointed out that the only completely satisfactory standard for a chemical comparison is the cargo oil prior to environmental exposure. Such a sample was not available.

In one field exercise a series of mousse samples was collected during the same day from the surface of the water adjacent to the Amoco Cadiz and at beaches from Portsall to Roscoff. The oil content of these samples was generally in the 30-40% range (Table 3-3). The samples were subsequently analyzed by extraction and direct GC analyses with no pre-GC sample fractionation to minimize loss of volatiles during handling.

The reference mousse treated in this fashion shows the dominant alkane as n-C_{11} (Fig. 3-6). The loss of volatiles is evident in samples collected as little as 2 km from the wreck site (Table 3-3) when the concentration of the lighter hydrocarbons is normalized to n-C_{24}. Fig. 3-7 demonstrates the loss of volatiles from a mousse collected at Meneham (NOAA-13), about 25 km from the wreck. The weathering trend is discontinuous with distance from the wreck, representing the variable input of fresh oil.

The light aromatics also show evidence of weathering as demonstrated in Figs. 3-8, 3-9, and 3-10 (see Table 3-4 for numbering of aromatic hydrocarbons in these figures). The concentration of internal standard (IS) is identical for all three samples. Mousse #13 shows considerable

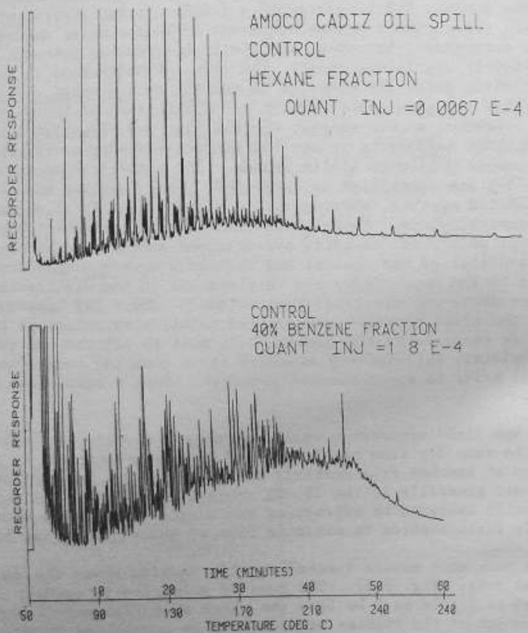


Figure 3-3. Computer-reconstructed high-resolution gas chromatogram of the n-hexane and 40%-benzene-in-n-hexane fractions of the medium Arabian crude oil sample (control). Peaks are identified in Figs. 3-4 and 3-5. (UNO-CBS)

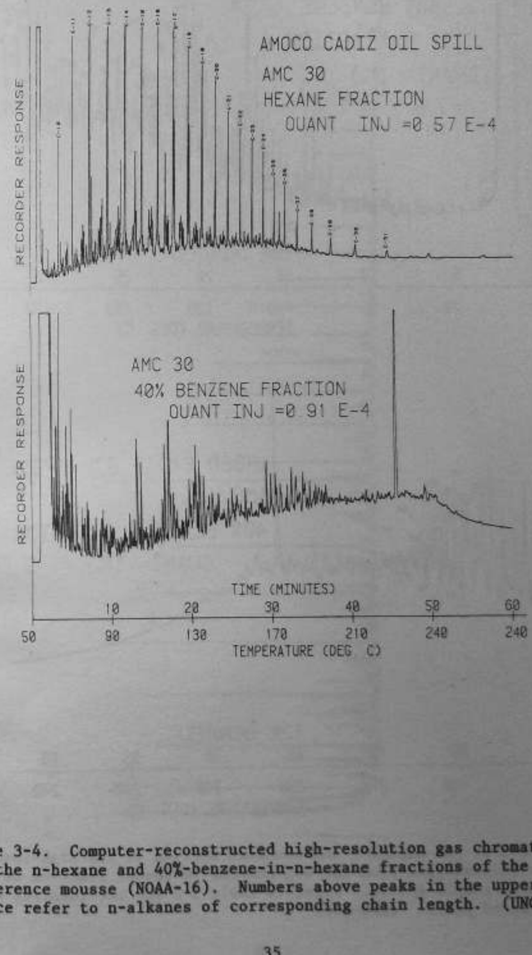


Figure 3-4. Computer-reconstructed high-resolution gas chromatograms of the n-hexane and 40%-benzene-in-n-hexane fractions of the reference mousse (NOAA-16). Numbers above peaks in the upper trace refer to n-alkanes of corresponding chain length. (UNO-CBS)

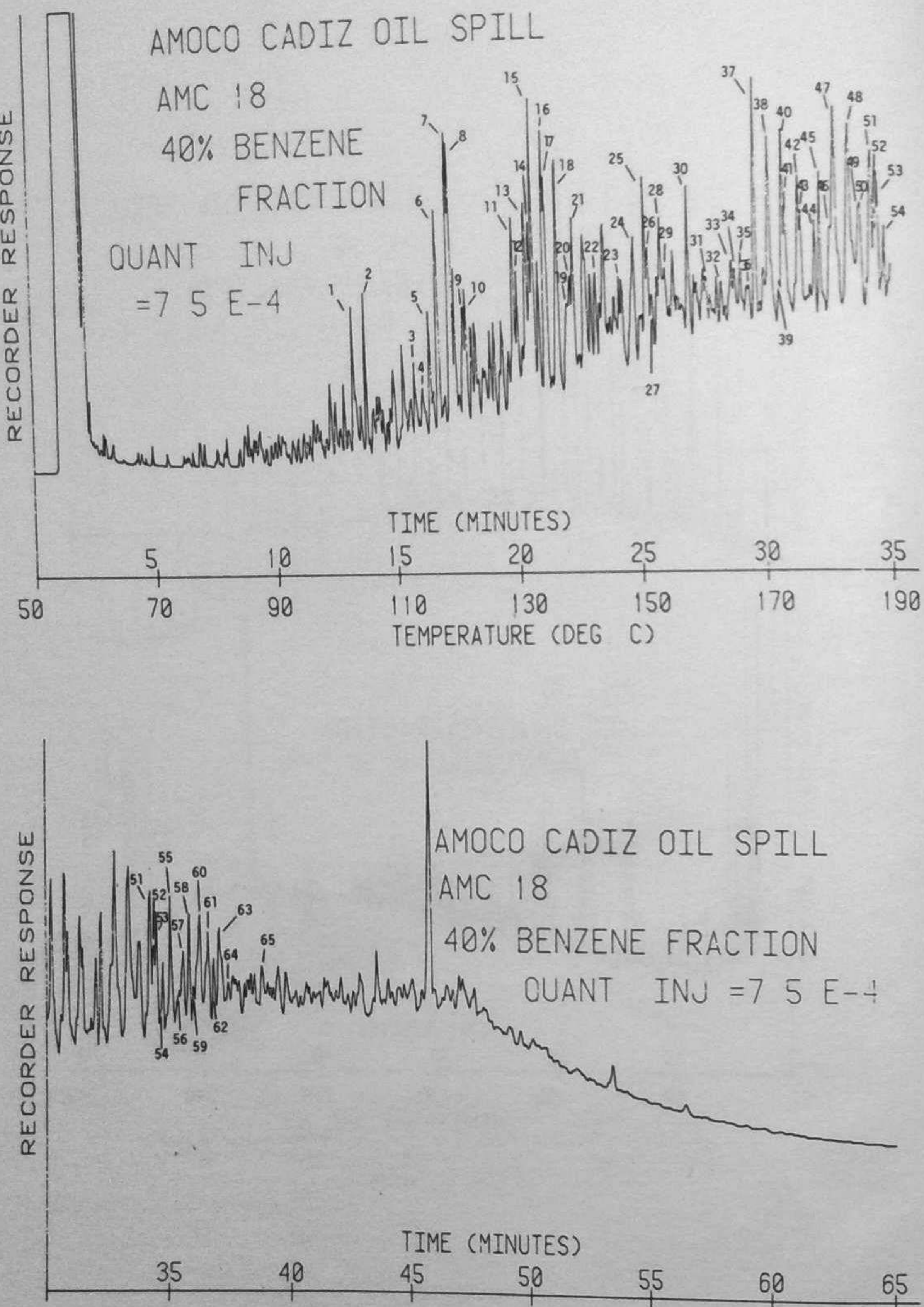


Figure 3-5. An expanded and numbered section of the high-resolution gas chromatogram from the 40%-benzene-in-hexane fraction of the mousse sample AMC-18. Refer to Table 3-2 for the identity of the numbered peaks. (UNO-CBS)

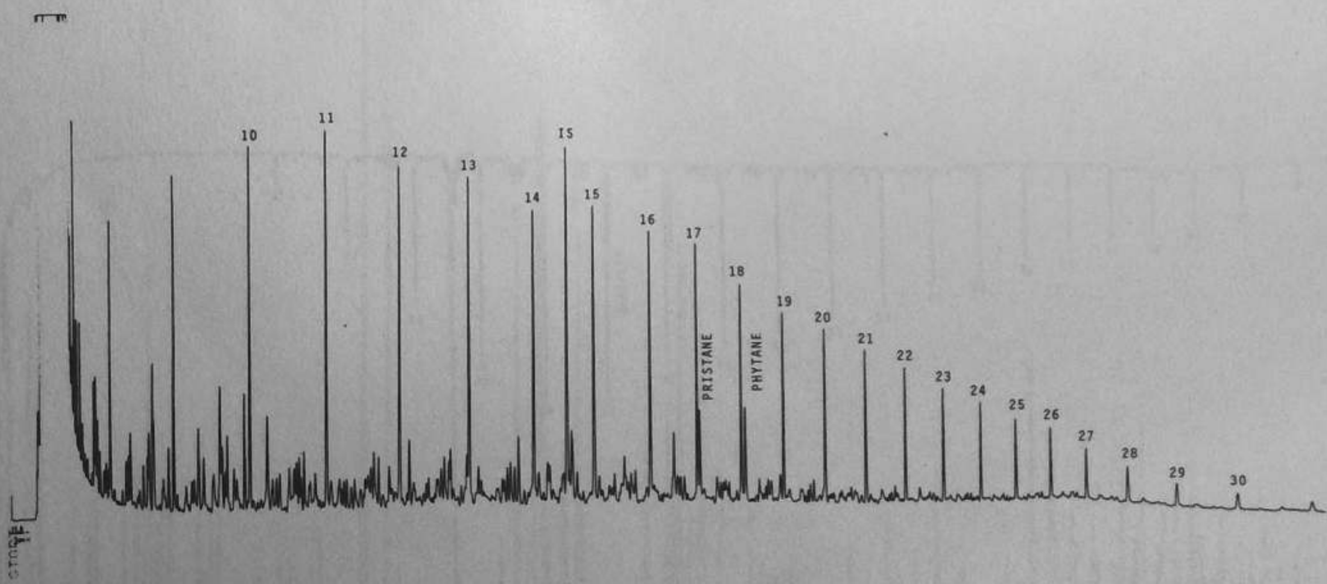


Figure 3-6. High-resolution gas chromatogram of a hexane solution of the reference mousse (NOAA-16). Numbers refer to n-alkanes of corresponding chain length. (NOAA-NAF)

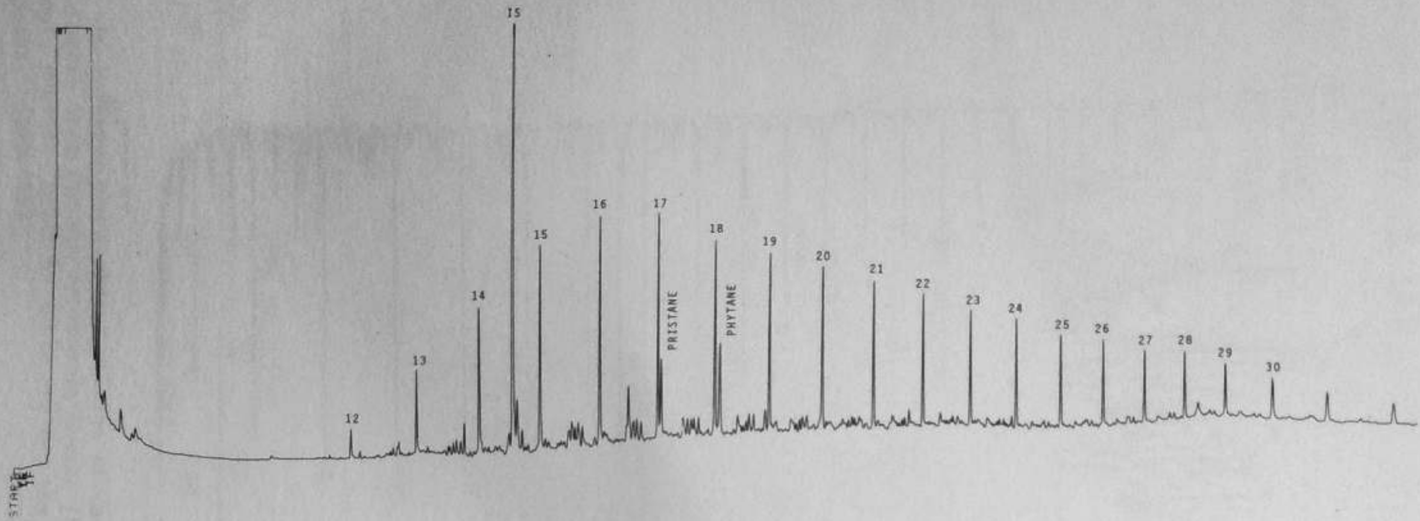


Figure 3-7. High-resolution gas chromatogram of an n-hexane solution of mousse NOAA-13, collected about 25 km from the wreck site. Numbers refer to n-alkanes of corresponding chain length. (NOAA-NAF)

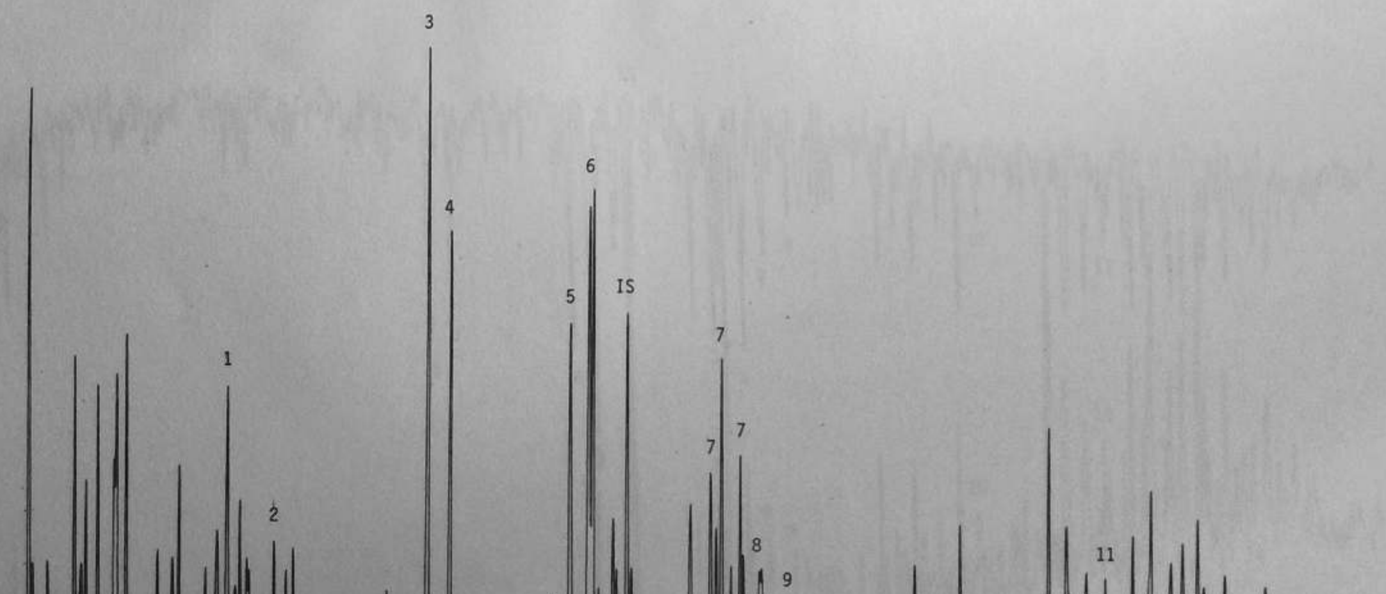


Figure 3-8. Gas chromatogram of the aromatic fraction of mousse sample #1, from the Amoco Cadiz oil spill. For peak identities see Table 3-4. (NOAA-NAF)

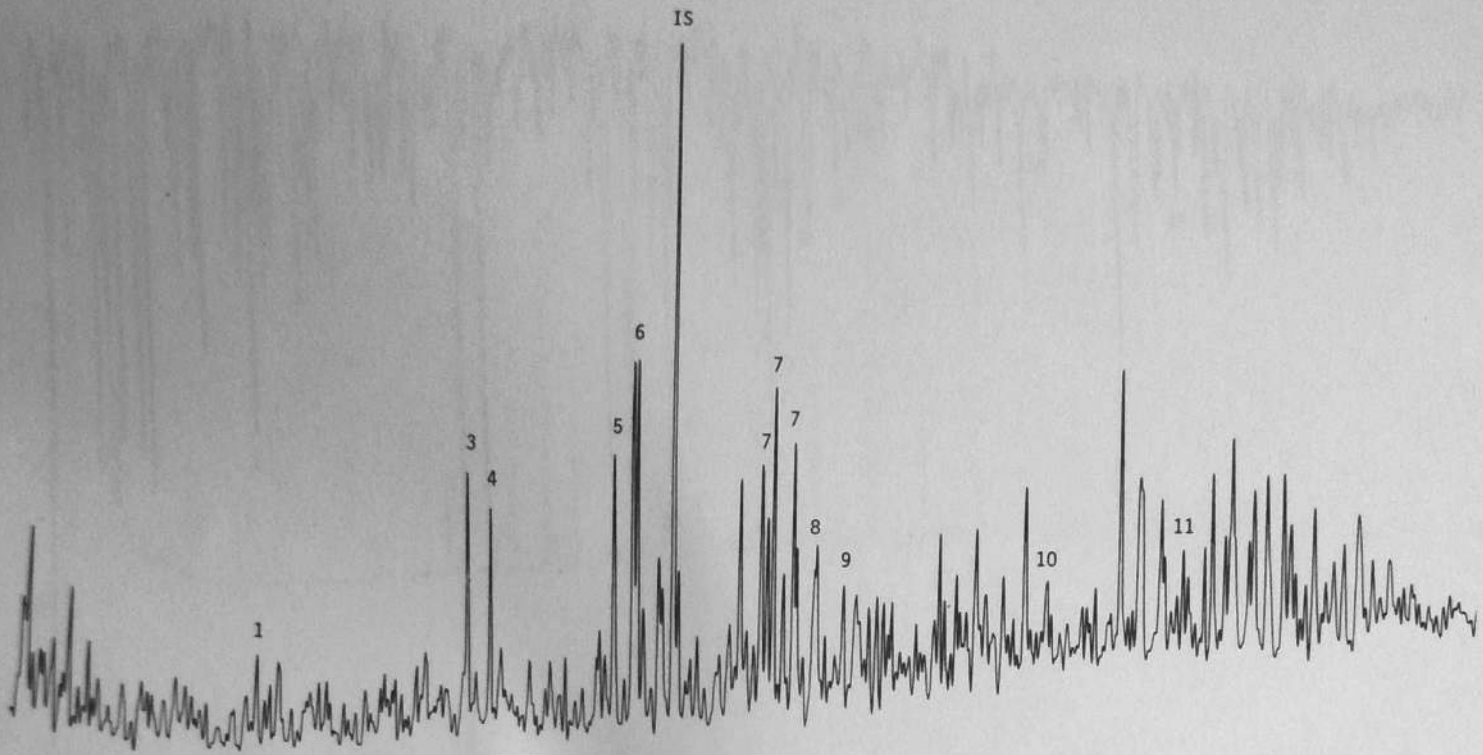


Figure 3-9. Gas chromatogram of the aromatic fraction of mousse sample #11, from the Amoco Cadiz oil spill. For peak identities see Table 3-4. (NOAA-NAF)

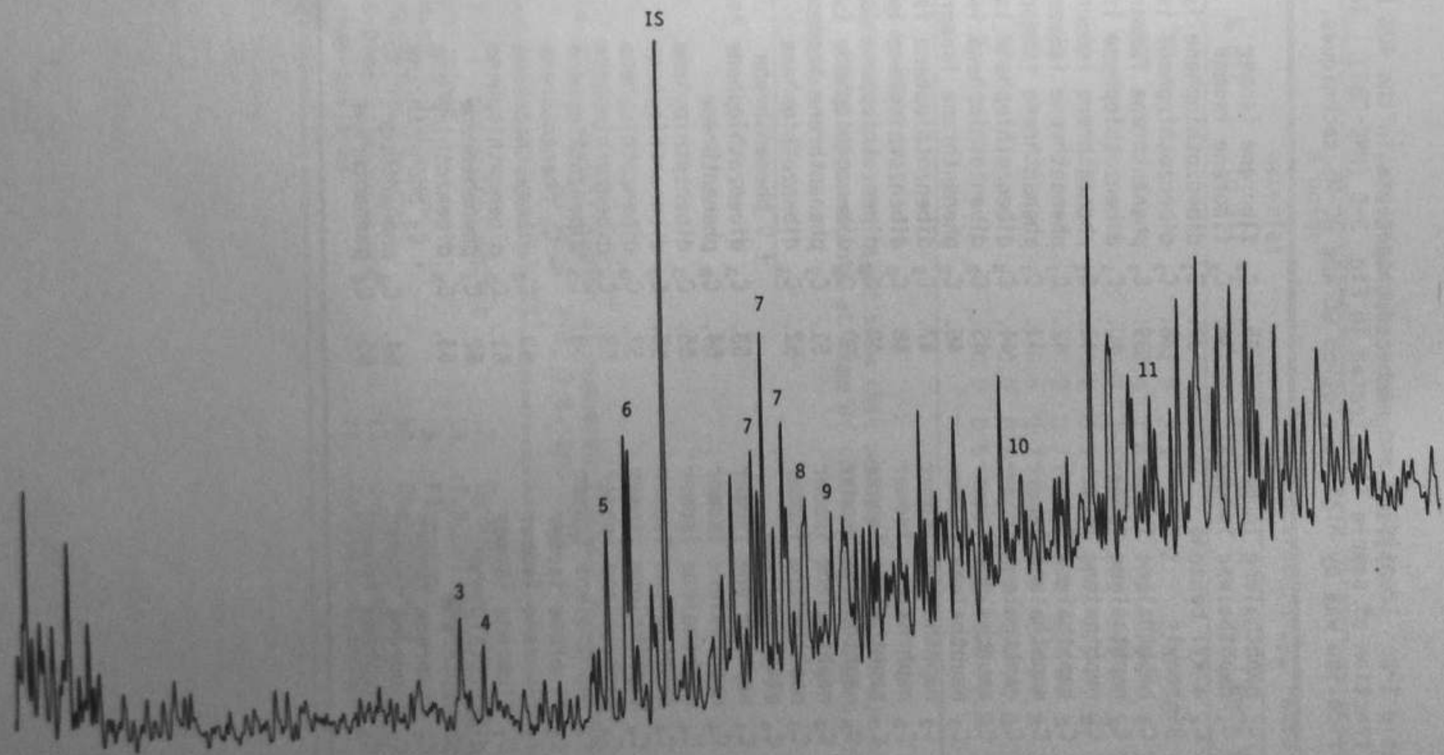


Figure 3-10. Gas chromatogram of the aromatic fraction of mousse sample #13, from the Amoco Cadiz oil spill. For peak identities see Table 3-4. (NOAA-NAF)

Table 3-2. Identified and numbered components in the 40% benzene fraction of sample illustrated in Fig. 3-5 (UNO-CBS). Identification was by high-resolution GC and GC-MS techniques.

1. C_1 naphthalene isomer
2. C_1 naphthalene isomer
3. C_4 alkyl benzene
4. Biphenyl
5. C_2 naphthalene isomer
6. C_2 naphthalene isomer
7. C_2 naphthalene isomer
8. C_2 naphthalene isomer
9. C_2 naphthalene isomer
10. C_2 naphthalene isomer
11. C_3 naphthalene isomer
12. C_3 naphthalene isomer
13. C_3 naphthalene isomer
14. C_3 naphthalene isomer
15. C_3 naphthalene isomer
16. C_3 naphthalene isomer
17. C_3 naphthalene isomer
18. C_3 naphthalene isomer
19. C_4 alkyl benzene
20. C_4 naphthalene isomer
21. C_4 naphthalene isomer
22. C_4 naphthalene isomer
23. C_4 naphthalene isomer
24. C_4 naphthalene isomer
25. C_4 naphthalene isomer
26. C_4 naphthalene isomer
27. C_1 fluorene isomer
28. C_1 fluorene isomer
29. C_1 fluorene isomer
30. dibenzothiphene
31. phenanthrene
32. C_2 fluorene isomer
33. C_2 fluorene isomer
34. C_2 fluorene isomer
35. C_2 fluorene isomer
36. C_2 fluorene isomer
37. C_1 dibenzothiophene isomer
38. C_1 dibenzothiophene isomer
39. C_1 phenanthrene isomer
40. C_1 dibenzothiophene isomer
41. C_1 phenanthrene isomer
42. C_1 phenanthrene isomer
43. C_1 phenanthrene isomer
44. C_2 dibenzothiophene isomer
45. C_2 dibenzothiophene isomer
46. C_2 phenanthrene isomer
47. C_2 dibenzothiophene isomer
48. C_2 dibenzothiophene isomer
49. C_2 dibenzothiophene isomer
50. C_2 dibenzothiophene isomer
51. C_2 phenanthrene isomer
52. C_3 dibenzothiophene + C phenanthrene
53. C_3 dibenzothiophene isomer
54. C_3 phenanthrene
55. C_3 dibenzothiophene
56. C_3 dibenzothiophene
57. C_3 dibenzothiophene
58. C_3 dibenzothiophene
59. C_3 dibenzothiophene + C_3 phenanthrene
60. C_3 dibenzothiophene
61. C_3 dibenzothiophene
62. C_3 phenanthrene
63. C_3 dibenzothiophene + C_3 phenanthrene
64. C_3 phenanthrene
65. C_3 phenanthrene

Table 3-3. Weathering of mousse[1]

Sample	% oil	% polar material in oil	Hydrocarbon/n-C_{24} ratio							
			C_{10}	C_{12}	C_{14}	C_{16}	C_{17}	Pris	C_{18}	Phyt
NOAA-16	30	-	1.9	2.3	2.3	2.3	2.0	1.0	1.9	1.4
NOAA-3	89[2]	9.1	0.4	1.6	2.0	2.2	1.9	0.8	1.8	1.2
NOAA-5	44	-	0.3	1.3	1.9	2.1	1.9	0.9	1.8	1.4
NOAA-7	40	16.2	0.0	0.1	0.5	1.4	1.5	1.0	1.6	1.7
NOAA-9	30	-	0.2	0.7	1.5	2.0	1.8	0.8	1.7	1.0
NOAA-11	26	21.1	0.5	1.2	2.7	3.6	2.4	0.9	2.1	1.2
NOAA-13	30	-	0.0	0.2	1.0	1.7	1.6	0.8	1.6	1.2
NOAA-15	31	-	0.0	0.6	1.6	2.2	2.0	0.8	1.8	1.2

[1] Analysis by NOAA-NAF

[2] Some water may have separated from this mousse during storage and transit. Field measurements at time of collection indicated 30% oil in this mousse.

Table 3-4. Identification of numbered aromatic hydrocarbons in Figs. 3-8, 3-9, and 3-10

1. 1,2,3,4-Tetramethylbenzene
2. Naphthalene
3. 2-Methylnaphthalene
4. 1-Methylnaphthalene
5. 2,6-Dimethylnaphthalene
6. C_2-Naphthalenes
7. C_3-Naphthalenes
8. 2,3,5-Trimethylnaphthalene
9. Fluorene
10. Phenanthrene
11. 1-Methylphenanthrene

IS. Internal standard

loss of aromatics from C_4-benzenes to C_3-naphthalenes compared to sample #1 (NOAA-1), collected at the wreck site. Sample #11, collected 10 km from the wreck, shows an intermediate loss of these molecules. Also demonstrated is the persistence of the phenanthenes and higher boiling components.

Further evidence of weathering processes is indicated in the polar content of the mousse-oil. The sample from Portsall (NOAA-3) contained 9% polars while the sample from les Grèves de Lilia (NOAA-11) contained 21% polars. Volatile oxygenated compounds were tentatively identified in a headspace analysis of NOAA-7, performed by NOAA-NAF. This sample had a definite H_2S smell when opened, indicating microbial activity in the mousse. Normal branched and aromatic ketones and aldehydes containing from 5 to 8 carbon atoms were indicated by GC-MS of the headspace. Confirmation with authentic standards is in progress. These data, if confirmed, would constitute solid evidence for the active oxidation of mousse, probably by microbial processes. Additional evidence on the production of polar material is presented in a following section. Continued and improved effort on the analytical chemistry of polar material is required to fully assess the environmental impact of spilled oil.

Examples of more pronounced weathering can be seen in Figures 3-11 and 3-12. AMC-14 represents a brown froth collected downslope from a mousse located on an open section of beach. As can be seen, the level of normal alkanes such as n-C_{17} and n-C_{18} have decreased almost to that of the level of the chromatographically adjacent isoprenoids. Also, there was a corresponding alteration in the chromatographic profile of the aromatics. By comparison, however, the most striking example of weathering was observed in sample F-82 which was collected from the surface of rocks along the mid-beach face near Pointe de Landunves. The native material appeared similar to tar, being dark and having a thick consistency. As can be seen in Fig. 3-11, phytane actually exceeds the concentration of n-C_{18}. Additionally, the presence of distinct aromatic components is difficult to observe.

Fig. 3-13 is a three-dimensional plot comparing the relative concentration (vertical axis) of selected aromatic hydrocarbons (axis into the page) in several similar samples, the reference mousse and the control oil (horizontal axis). The concentration of components within a sample is displayed relative to the concentration of dibenzothiophene which was given a value of 100. "A" and "B" (Table 3-5) are the medium Arabian crude oil and NOAA-16 reference mousse respectively. Careful examination of the three-dimensional plot shows remarkable similarity in the distribution of aromatic components in the Arabian crude and the NOAA-16 mousse samples. Additionally, these profiles are consistent in all mousse samples analyzed except sample "E" (AMC-14) and sample "J" (F-82). These data clearly display the greater degree of environmental modification in these two samples when compared to the others.

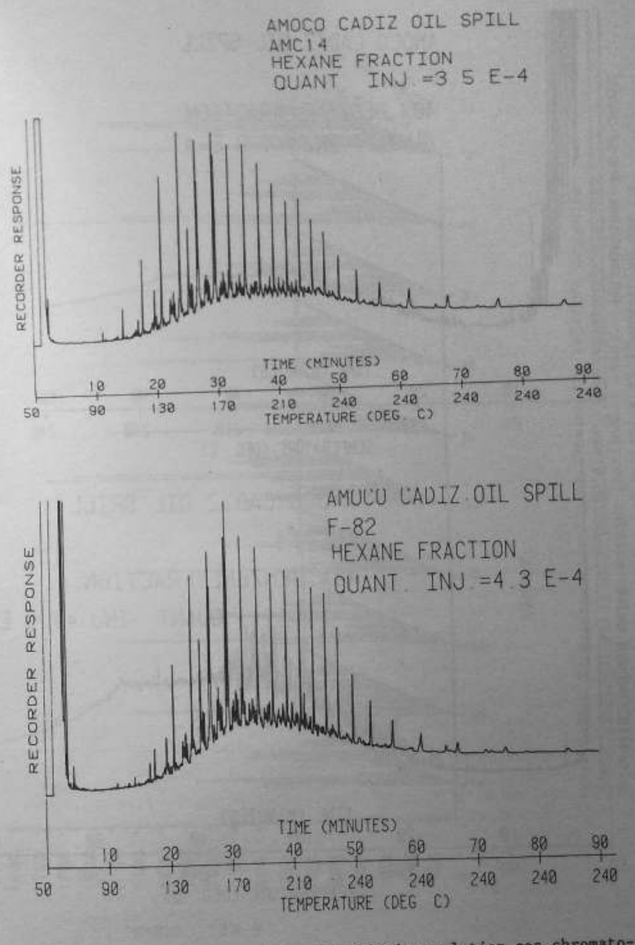
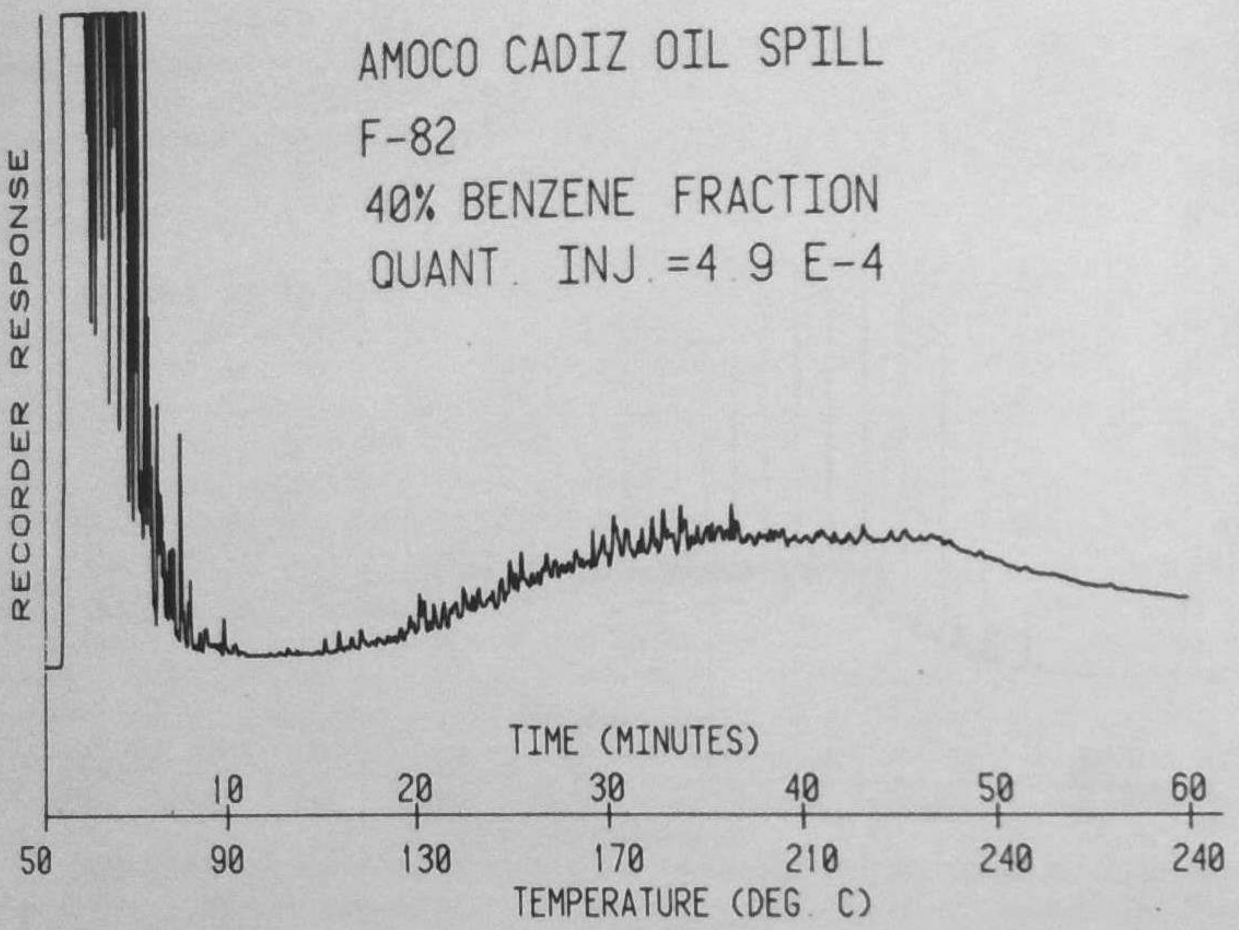


Figure 3-11. Computer-reconstructed high-resolution gas chromatograms of the hexane fractions of samples AMC-14 and F-82. (UNO-CBS)



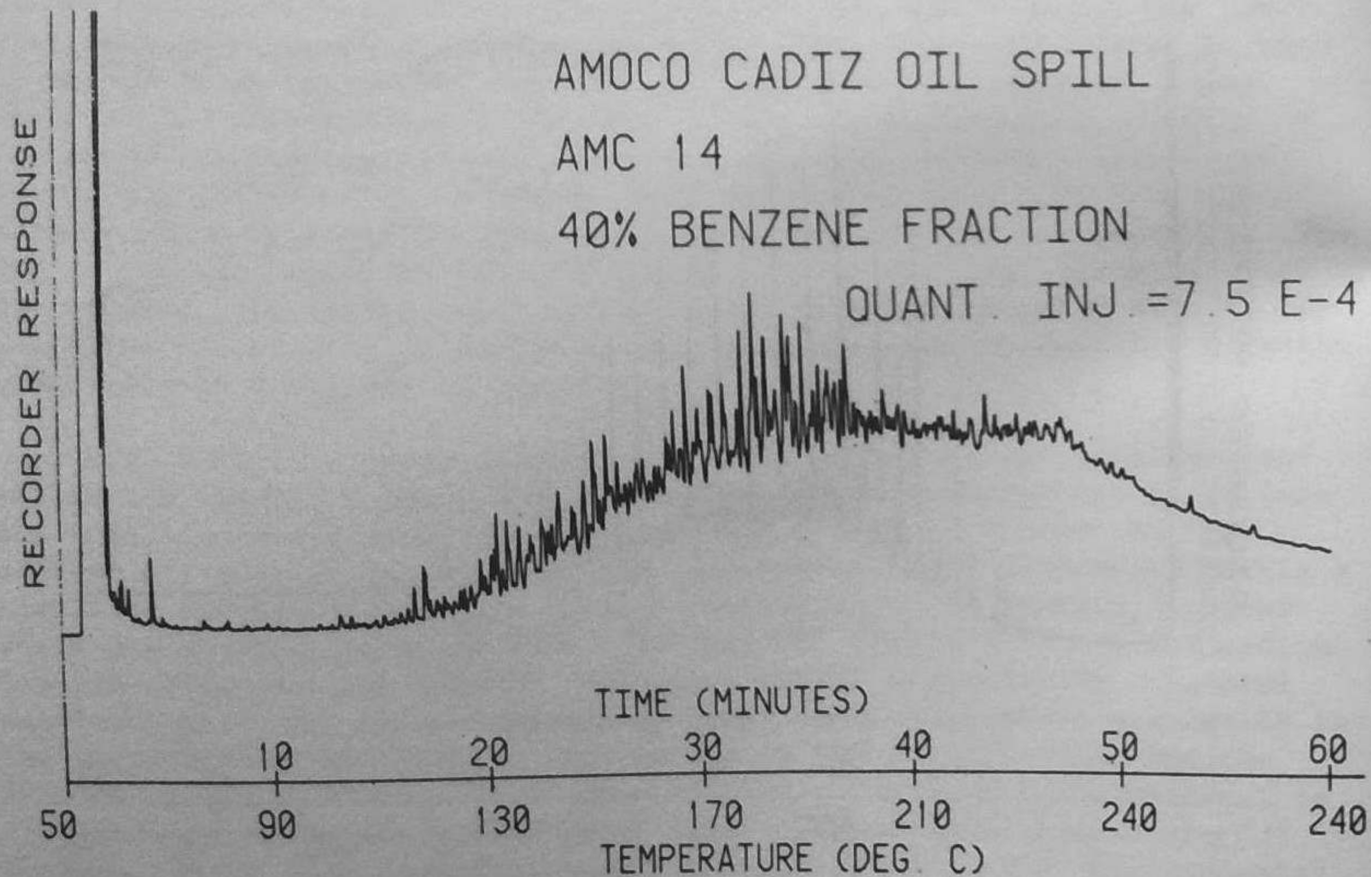


Figure 3-12. Computer-reconstructed high-resolution gas chromatograms of the 40%-benzene-in-hexane fractions of samples AMC-14 and F-82. (UNO-CBS)

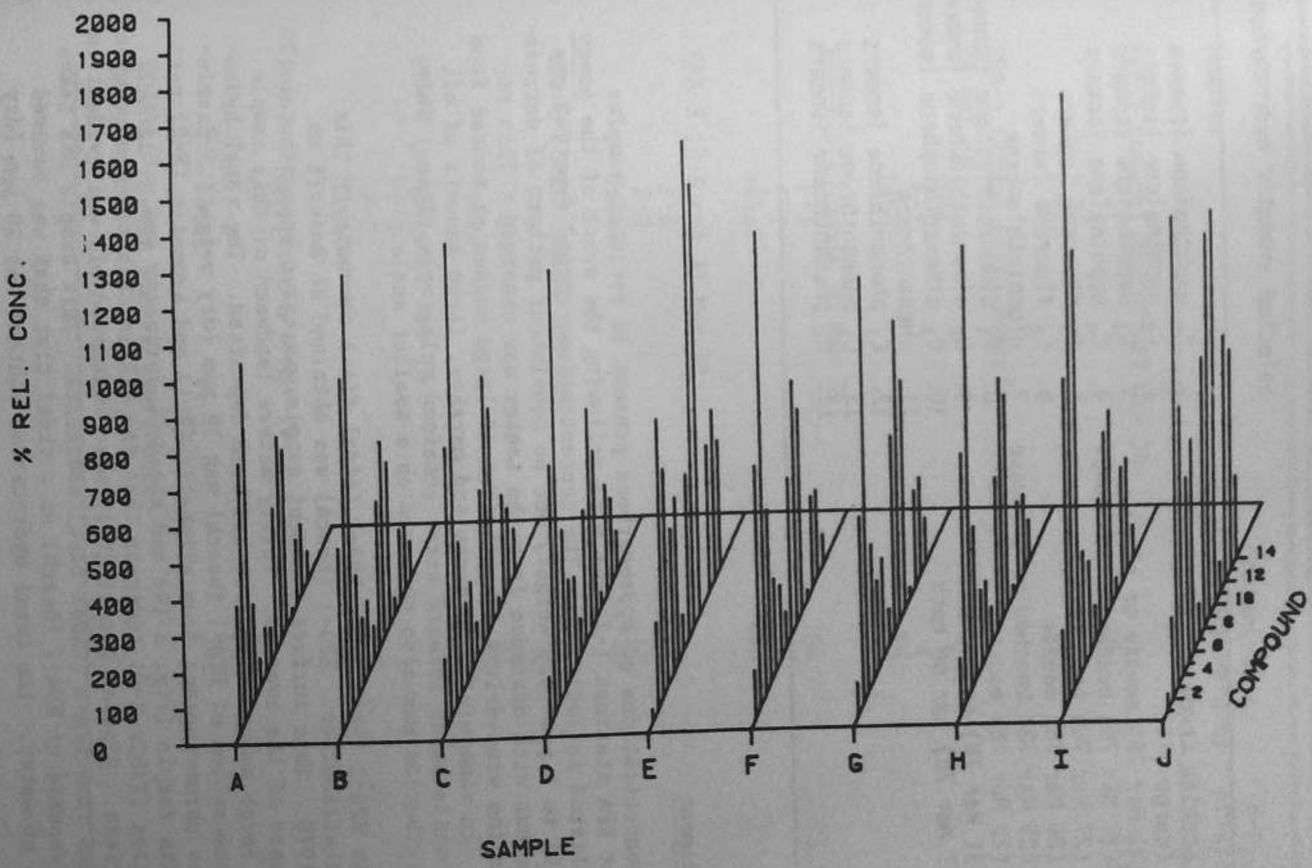


Figure 3-13. Three-dimensional plot showing the relative concentrations (vertical axis) of selected aromatic hydrocarbons (axis into page) in certain mousse samples (horizontal axis). All components are compared relative to the concentration of dibenzothiophene in each sample. Refer to Table 3-5 for identification of samples and aromatic hydrocarbons. (UNO-CBS)

Table 3-5. Identification of samples and selected aromatic hydrocarbons displayed in Fig. 3-13 (UNO-CBS)

Samples	Selected aromatic hydrocarbons
A. Medium Arabian crude oil (Control)	1. C_1 naphthalene isomers
B. AMC-30 (cargo oil)	2. C_2 naphthalene isomers
C. AMC-1 (31 Mar 78) mousse or slick	3. C_3 naphthalene isomers
D. AMC-12 (27 Mar 78) beached oil, mousse	4. C_4 naphthalene isomers
E. AMC-14 (27 Mar 78) brown froth	5. C_1 fluorene isomers
F. AMC-16 (28 Mar 78) mousse	6. C_2 fluorene isomers
G. AMC-17 (29 Mar 78) beached oil, mousse	7. dibenzothiophene
H. AMC-18 (29 Mar 78) mousse	8. C_1 dibenzothiophene isomers
I. AMC-3 (31 Mar 78) sediment	9. C_2 dibenzothiophene isomers
J. F-82 (31 Mar 78) tar on rock	10. C_3 dibenzothiophene isomers
	11. phenanthrene
	12. C_1 phenanthrene isomers
	13. C_2 phenanthrene isomers
	14. C_3 phenanthrene isomers

3.3.2 Sediment

The concentrations of hydrocarbons present in sediment samples obtained at EPA stations 1-7 (see map) following the wreck of the Amoco Cadiz are listed in Table 3-6. The concentrations ranged from 742 ppm (dry weight) to 4 ppm (dry weight) but no consistent pattern of decreasing oil content with distance from the tanker was observed. This resulted from the wind-driven distribution of large masses of mousse from the wreck. In some windbound coves and marshes, large amounts of oil collected, while other leeward areas remained relatively clean. This patchy distribution was also observed on a smaller scale.

Samples EPA-1 (beach) and EPA-1 (tidal flat) demonstrate this irregular distribution. EPA-1 (beach) was obtained at Roscoff on March 27, 1978. This surface sediment sample was taken approximately 70 meters seaward of the seawall. Thirty meters landward of this sample location a large amount of mousse had been deposited. The total hydrocarbon concentration of EPA-1 (beach) was 79 ppm (dry weight). Examination of gas chromatograms from aliphatic (F-1) and aromatic (F-2) portions of this sample (Fig. 3-14) and the n-C_{17}/pristane and n-C_{18}/phytane ratios (Table 3-6) indicate that the oil in this sediment sample was quite fresh. Similar but slightly more weathered oil was evident in chromatograms from EPA-1 (tidal flat) sediments. This sample was taken 200 meters seaward of EPA-1 (beach) on a tidal flat that was covered with ≅ 2 cm of water. Its total hydrocarbon content was 10 ppm (dry weight).

Table 3-6. Sediments

Samples	Concentration µg/g (dry weight)	n-C_{17}/ pristane	n-C_{18}/ phytane
EPA-1 (beach) Roscoff 27 Mar 78			
F-1	65	3.1	2.0
F-2	14		
Total	79		
EPA-1 (tidal Flat) Roscoff 27 Mar 78			
F-1	6	-	1.5
F-2	4		
Total	10		
EPA-2 Ile Grande 30 Mar 78			
F-1	164	1.7	2.6
F-2	62		
Total	226		
EPA-3 (0-5 cm) 31 Mar 78			
F-1	5	0.9	0.7
F-2	20		
Total	25		
EPA-3 (5-10 cm) 31 Mar 78			
F-1	31	.7	-
F-2	17		
Total	48		
EPA-4 Locquirec 2 Apr 78			
F-1	3	1.3	0.8
F-2	1		
Total	4		
EPA-7 l'Aber Wrac'h 6 Apr 78			
F-1	539	0.5	0.4
F-2	203		
Total	742		
NOAA-16 Mousse sample (reference) 26 Mar 78			

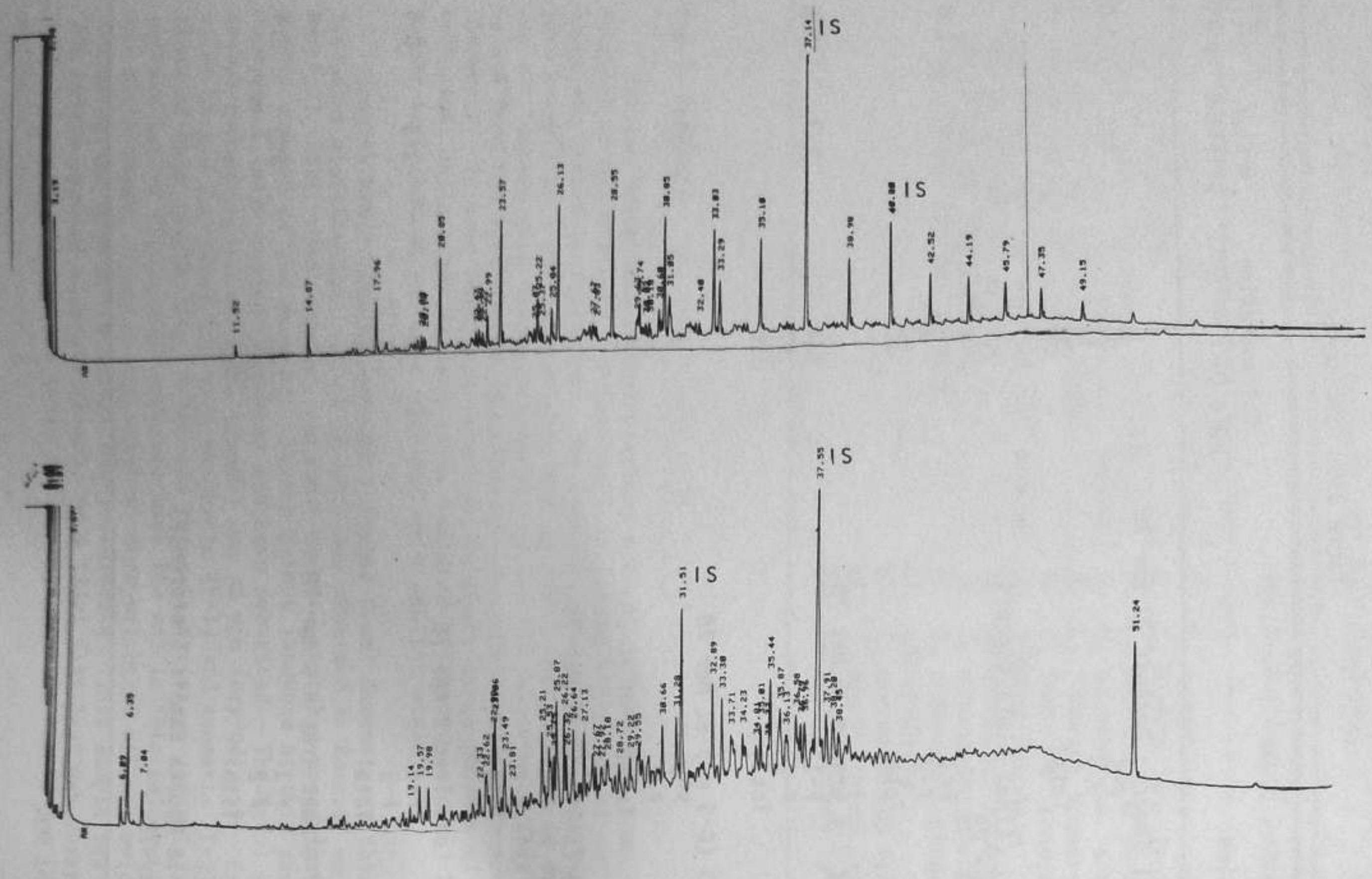


Figure 3-14. Gas chromatograms of aliphatic (upper trace) and aromatic (lower trace) fractions obtained from sediment at EPA-1 (beach--Roscoff) on March 27, 1978. Internal standards marked IS. (EPA-ERLN)

From these limited data it appeared that as the mousse was rafted over the tidal flat a relatively small amount of incorporation of oil into the sediments occurred. As the mousse moved shoreward, the combination of decreasing water depth and increasing wave action caused more incorporation of oil into sediments at the lower beach face. Finally, the mousse was deposited on the top portion of the beach.

A core sample obtained at EPA-3 on March 31, 1978, was cut into a 0-5 cm and a 5-10 cm section. The concentrations of total hydrocarbons were 25 ppm (dry weight) in the 0-5 cm section, and 48 ppm (dry weight) in the 5-10 cm section. While gas chromatograms from the aliphatic (F-1) and aromatic (F-2) portions of both core sections were similar (0-5 cm F-1 and F-2 chromatograms shown in Fig. 3-15), the proportions of hydrocarbons present in the aliphatic and aromatic fractions were different (Table 3-6). The cause of these differences is unknown, but may have resulted from the incorporation of dispersed oil droplets from the overlying water. The water sample obtained at the location was tinted brown and contained 42 ppm hydrocarbon material.

The highest concentrations of oil were found in sediment samples from heavily polluted l'Aber Wrac'h (Plate 3-6) (EPA-7) and the oiled marsh Ile Grande (EPA-2). At Ile Grande oil and mousse were scraped from the sediment surface before the sample was taken. The lowest concentration observed in sediment samples was obtained on the beach at Locquirec (EPA-4). Landward of this sample location large quantities of mousse had accumulated. Presumably this low value reflected the small-scale patchy distribution of oil in sediments of this area.

Table 3-6 lists the n-C_{17}/pristane and n-C_{18}/phytane ratios calculated from gas chromatograms of the sample extracts. These ratios may be utilized to determine the bacterial degradation of the n-alkanes present in petroleum, because bacteria degrade straight chain alkanes (i.e., n-heptadecane and n-octadecane) more rapidly than the branched chain isoprenoids pristane (2, 6, 10, 14-tetramethylpentadecane) or phytane (2, 6, 10, 14-Tetramethylhexadecane). No consistent pattern is observed relating the distance from the wreck to the amount of bacterial degradation of petroleum present in the sediment samples. There are several possible explanations for this inconsistency:

(1) The oil leaked from the wreck for a period of about two weeks, which resulted in different lengths of environmental exposure for oil in the sediments sampled.

(2) The spilled oil contaminated different sediments. Its path from the tanker may have varied.

(3) Variations may have existed in the amount of oil present in sediments relative to the bacterial population able to degrade the oil.

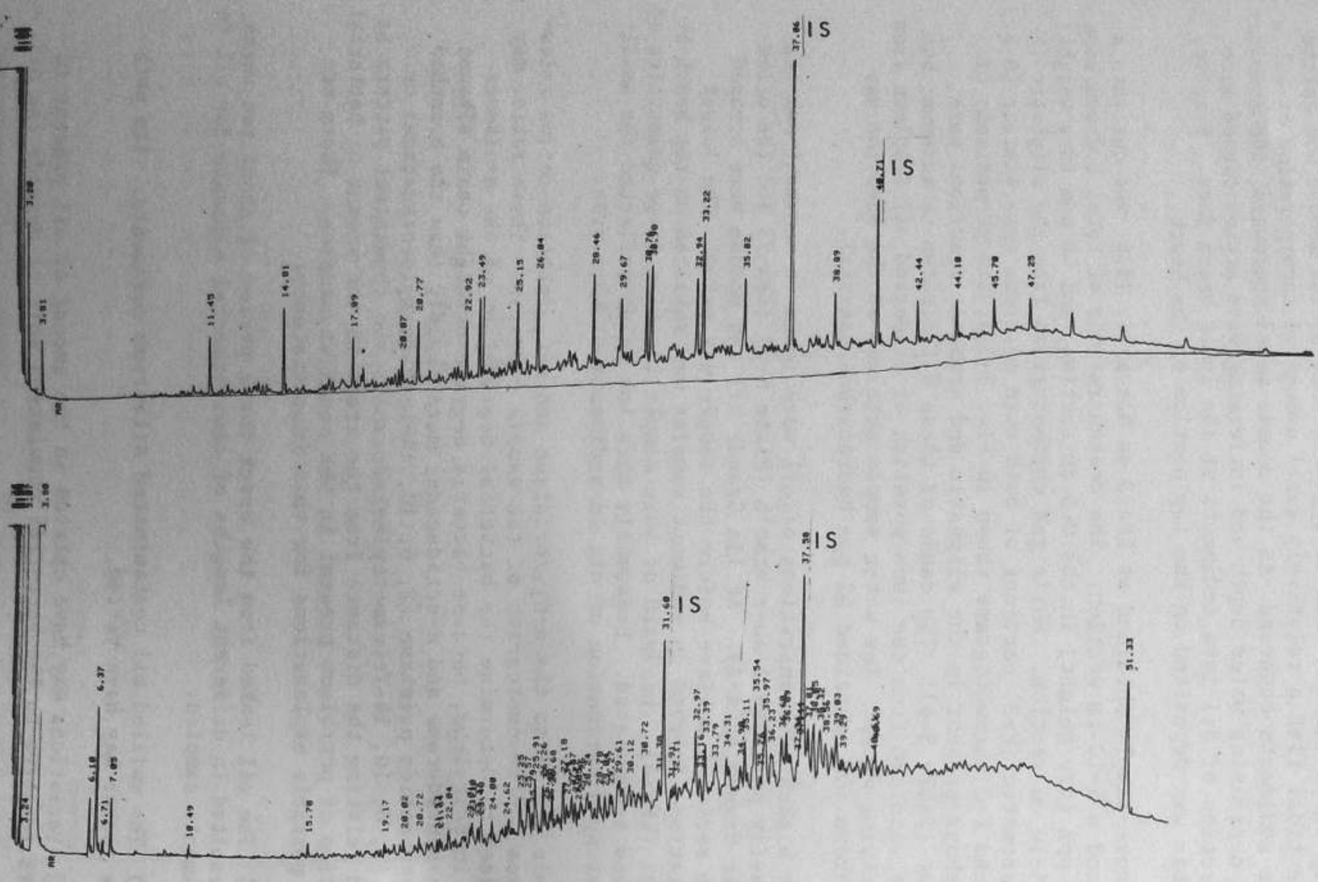


Figure 3-15. Gas chromatograms of aliphatic (upper trace) and aromatic (lower trace) fractions obtained from 0-5 cm section of sediment core obtained at EPA-3 on March 31, 1978. Internal standards marked IS. (EPA-ERLN)

Similar variations in degradation were observed in soil and sediments taken on a vertical transect up a cliff at l'Aber Benoit. Reconstructed gas chromatograms obtained from the aliphatic and aromatic fractions of these samples are shown in Figs. 3-16 and 3-17. These figures show that relatively low levels of aliphatic and aromatic hydrocarbons were found in the soil sample taken above the high water mark on the face of the cliff. The chromatograms of this sample were not similar to those obtained for contaminated samples, indicating that the oil did not impact this soil. Chromatograms obtained from sediments taken 30 cm below the high water mark and at the base of the cliff showed the presence of petroleum hydrocarbons in the aliphatic and aromatic fractions. Comparisons of these chromatograms indicated that the oil in the sediments at the cliff base was more weathered than the oil from sediments on the face of the cliff. The increased weathering is shown in the chromatograms of sediments at the cliff base by a decrease in the peak heights of n-C_{17} and n-C_{18} relative to the isoprenoids, pristane and phytane, in the aliphatic fraction, and a decrease in resolved vs. unresolved components in the aromatic fractions. Again, this sample series shows that variations in weathering of oil occur in samples taken only a few meters apart, but, due to the continuous leakage of oil from the wreck, the length of time that the oil was present in these samples may have been different.

Fig. 3-18 shows a three-dimensional plot of the concentration of selected aromatics in these cliff samples. This figure also demonstrates that concentrations of these aromatics were below detection limits in the upper cliff soil sample, and shows the variation in distribution of these aromatics on the cliff face and in the sediments at the cliff base.

3.3.3 Photochemical Processes

Figure 3-19 shows the high-resolution gas chromatograms of the methanol fractions from AMC-12, AMC-14, AMC-16, AMP-1 (photolyzed medium Arabian crude oil), and AMP-C (nonphotolyzed medium Arabian crude oil). The presence of a complex unresolved mixture (hump) in the photolyzed control sample and the two environmental samples, with absence of any significant hump in the unphotolyzed control sample, provides indirect evidence for photo-oxidation processes in the environmentally exposed mousse samples. Additional evidence was obtained by inspection of mass chromatograms of the ion fragments characteristic of the sulfoxides of dibenzothiophene and its n-C_1 and n-C_2 alkyl homologs in the same methanol fractions. Ion fragments thought to be associated with the complete series of sulfoxides were observed. The presence of substantially higher quantities of the sulfoxides in the methanol fractions of the environmentally derived mousse samples and the photolyzed control oil sample was confirmed by comparison of the full mass spectra in each sample with authentic standards.

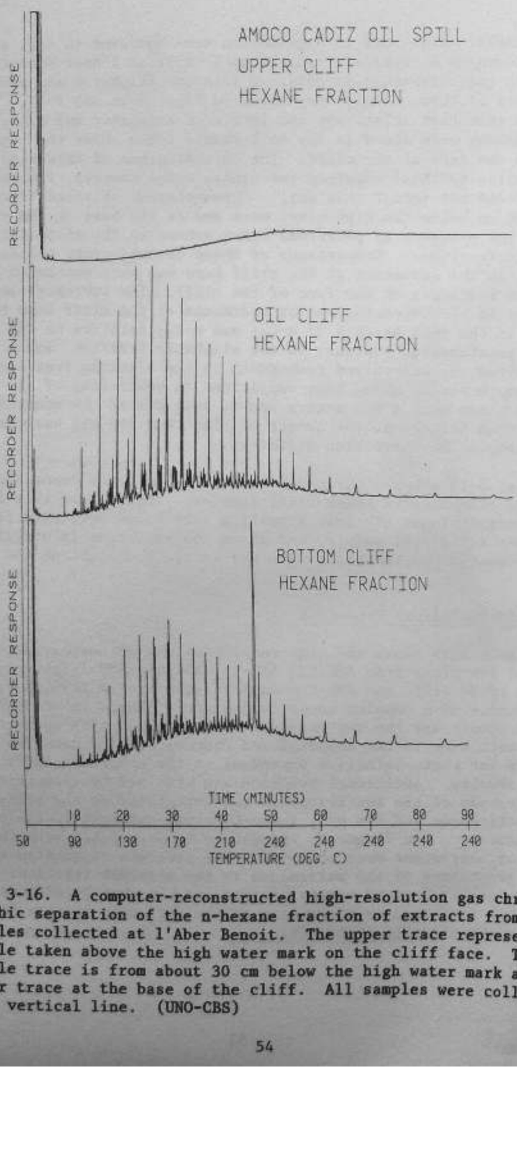


Figure 3-16. A computer-reconstructed high-resolution gas chromatographic separation of the n-hexane fraction of extracts from soil samples collected at l'Aber Benoit. The upper trace represents a sample taken above the high water mark on the cliff face. The middle trace is from about 30 cm below the high water mark and the lower trace at the base of the cliff. All samples were collected in a vertical line. (UNO-CBS)

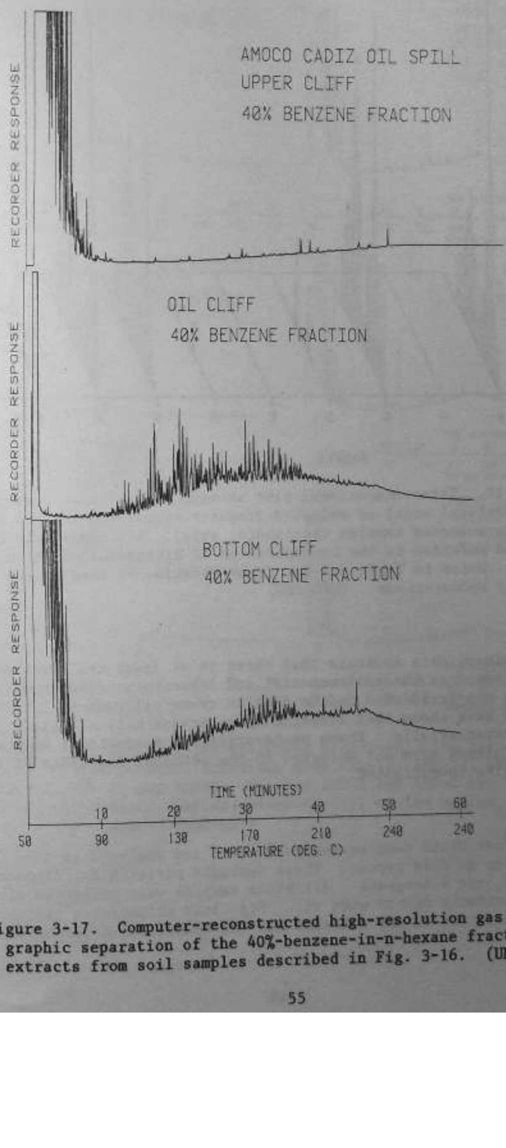


Figure 3-17. Computer-reconstructed high-resolution gas chromatographic separation of the 40%-benzene-in-n-hexane fraction of extracts from soil samples described in Fig. 3-16. (UNO-CBS)

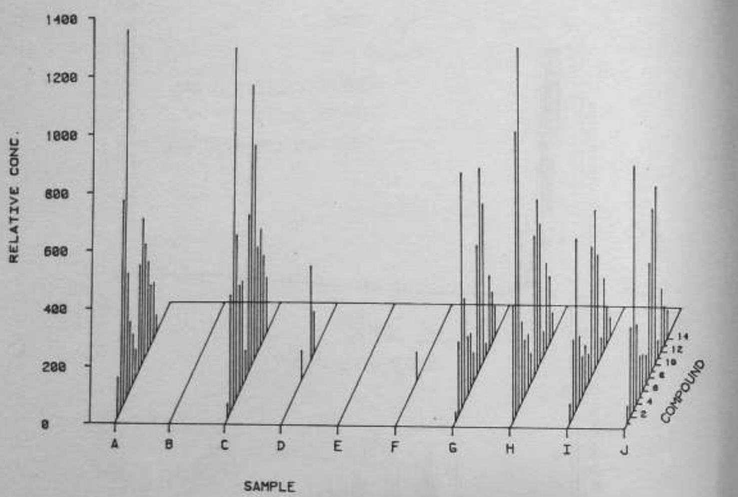


Figure 3-18. Three-dimensional plot showing the relative concentration (vertical axis) of selected aromatic hydrocarbons (axis into page) in selected samples (horizontal axis). All components are compared relative to the concentration of dibenzothiophene in each sample. Refer to Table 3-7 for identification of samples and aromatic hydrocarbons. (UNO-CBS)

Preliminary data indicate that there is at least ten times more oxidized product in the environmental and laboratory-irradiated samples than in the non-irradiated medium Arabian crude oil control. Further experiments have shown that aromatic hydrocarbons will stimulate photo-oxidation substantially. Known photo-oxidation products of naphthalenes and phenanthrenes were not detected in the methanol fractions of the two mousse samples investigated.

3.3.4 Biota

Only four biota samples were extracted and analyzed in time for incorporation in this report. These included periwinkles, limpets, polychaetes, and a seagrass. All biota samples were collected alive and were not obviously coated with oil. Fig. 3-20 illustrates the chromatographic separation of the n-hexane and 40%-benzene-in-n-hexane fractions

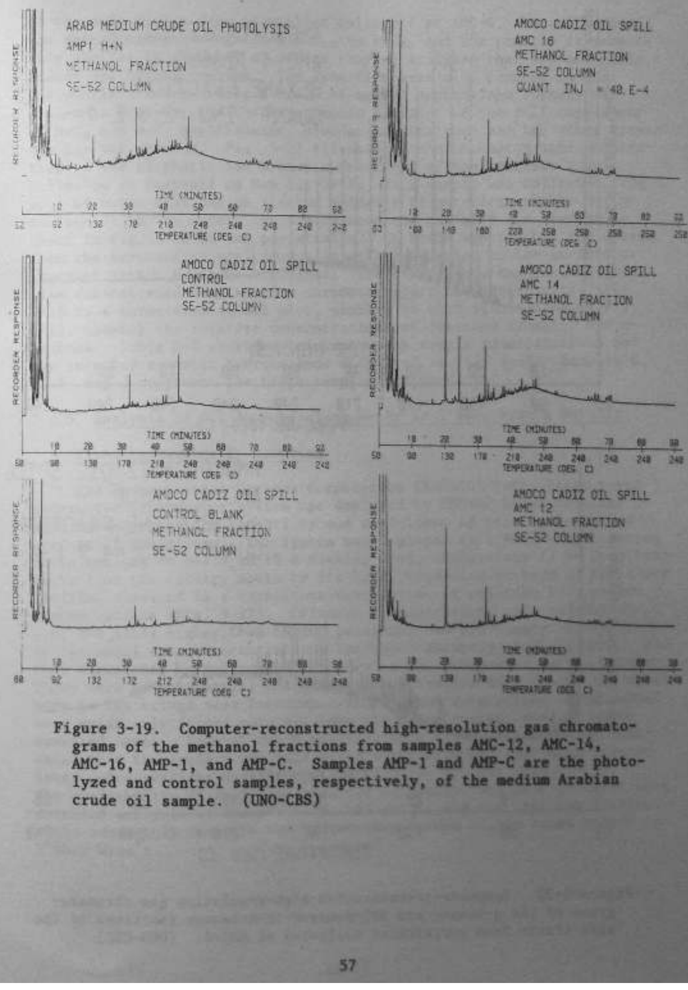


Figure 3-19. Computer-reconstructed high-resolution gas chromatograms of the methanol fractions from samples AMC-12, AMC-14, AMC-16, AMP-1, and AMP-C. Samples AMP-1 and AMP-C are the photolyzed and control samples, respectively, of the medium Arabian crude oil sample. (UNO-CBS)

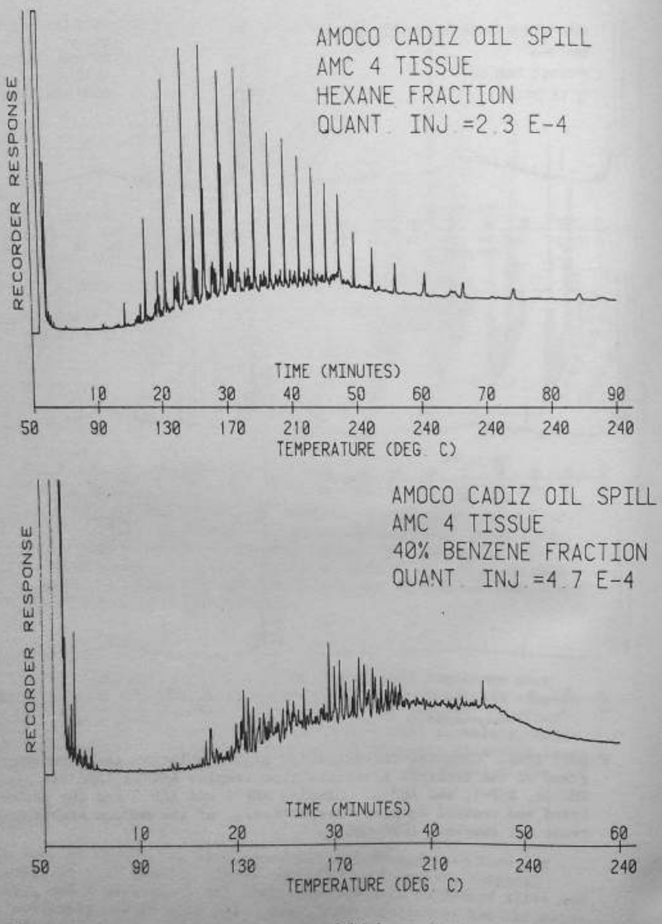


Figure 3-20. Computer-reconstructed high-resolution gas chromatograms of the n-hexane and 40%-benzene-in-n-hexane fractions of the soft tissue from periwinkles collected at AMC-4. (UNO-CBS)

of the soft tissue from perwinkles collected at AMC-4. As can be seen, the normal alkanes range from n-C_{13} to n-C_{33} and the profile is remarkably similar to a number of mousse samples analyzed that had undergone a modest weathering process. The aromatics were also present in the periwinkle tissues. Only a trace of methyl naphthalene isomers was present. However, the chromatographic profiles of the full complement of n-C_2 and n-C_3 naphthalenes, dibenzo-naphthalenes and the other aromatics are ver obvious. Fig. 3-21 illustrates the chromatographic separation of the aliphatic and aromatic fractions of the seagrass sample collected at Portsall on May 31, 1978. This sample was collected from a pool of water that had no visible evidence of petroleum either on the surface or in the water. As can be seen the profiles are similar to those in Fig. 3-20 in the periwinkles. It would appear that the mousse from the surrounding environment is either absorbed on the surface or ingested intact by these organisms. The other biota samples analyzed also demonstrated very similar chromatographic characteristics. Fig. 3-18 is a three-dimensional plot, similar to that illustrated in Fig. 3-13, showing the relative concentrations of selected aromatic hydrocarbons. Table 3-7 provides information on sample identification and the selected aromatic hydrocarbons displayed in Fig. 3-18. Samples G, h, I, and J represent the biota samples analyzed.

3.3.5 Analysis of Oil in Subsurface Water in l'Aber Wrac'h Estuary

Towed Underwater Fluorometer

The Environmental Devices Corporation (ENDECO) Petro Track towed underwater fluorometer system was deployed by ENDECO under contract to NOAA to determine the capability and usefulness of this system under real spill conditions. The system was deployed in l'Aber Wrac'h during three cruises on board an 18 m fishing boat. Subsurface (1 to 3 m) transects from the estuary mouth to its head, conducted on each of the three cruises, resulted in a consistent description of relative hydrocarbon concentrations (Fig. 3-22). Offshore concentrations were relatively low, but still higher than ENDECO personnel had previously experienced. At the shoal area, concentrations increased abruptly about fivefold, and then diminished to intermediate values as one progressed up the estuary. There were no substantial changes in concentration from inside the shoal area to the bridge near Paludenn. The violent wave action in the shoal area apparently forced more oil into the water column, some of which remained there. Several depth profiles were taken, all of which indicated that the estuary was well mixed vertically and that high oil-in-water concentrations were in contact with the benthos (Fig. 3-23). The availability of real-time relative concentrations made it clear that detailed analysis at one offshore, one shoal, and one upstream station would adequately describe the hydrocarbon burden of the water column in l'Aber Wrac'h.

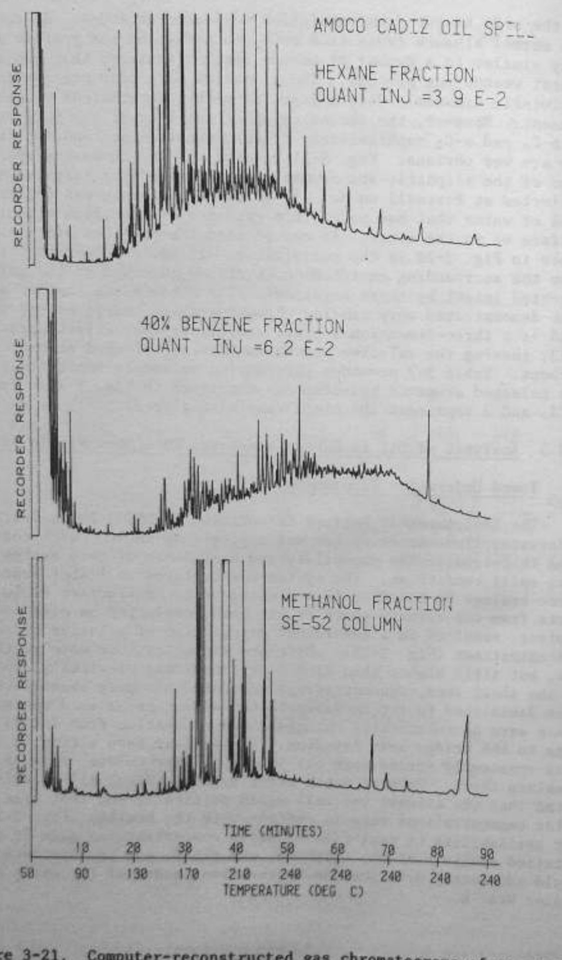


Figure 3-21. Computer-reconstructed gas chromatograms of seagrass collected near Portsall. (UNO-CBS)

Table 3-7. Three-dimensional plot of the concentration (vertical axis) of selected aromatic hydrocarbons (axis into page) for certain Amoco Cadiz samples (horizontal axis) as shown in Fig. 3-18 (UNO-CBS)

Samples		Selected aromatic hydrocarbons	
A.	Oil Cliff	1.	C_1 naphthalene isomers
B.	Upper Cliff	2.	C_2 naphthalene isomers
C.	Bottom Cliff	3.	C_3 naphthalene isomers
D.	AMC-1, ground water	4.	C_4 naphthalene isomers
E.	AMC-3, ground water	5.	C_1 fluorene isomers
F.	AMC-17, ground water	6.	C_2 fluorene isomers
G.	AMC-4, periwinkles	7.	dibenzothiophene
H.	AMC-17, limpets	8.	C_1 dibenzothiophene isomers
I.	AMC-18, polychaetes	9.	C_2 dibenzothiophene isomers
J.	Seagrass	10.	C_3 dibenzothiophene isomers
		11.	phenanthrene
		12.	C_1 phenanthrene isomers
		13.	C_2 phenanthrene isomers
		14.	C_3 phenanthrene isomers

Concentrations reported by the towed fluorometer varied from 2 to 21 times the concentrations derived from discrete water samples. The towed fluorometer reading appeared to have a compressed dynamic range. The towed fluorometer was calibrated with a diluted oil-in-water emulsion. The difficulty involved in preparing such a mixture in a quantitative way is undoubtedly partly responsible for the sometimes large discrepancies between the concentrations derived from the towed fluorometer and those from discrete water samplings.

UV-Fluorescence Analysis of Water Samples Collected in l'Aber Wrac'h

Simultaneously with the deployment of the towed fluorometer, discrete samples were collected with Niskin sterile bag samplers. The sampler was positioned just in front of the towed fluorometer intake to facilitate comparison of the results from the two methods. Water samples were removed from the bags immediately after retrieval and stored in hexane-rinsed glass jugs with Teflon-lined caps. Samples were extracted in the laboratory within 36 hours.

The first transect up the estuary (March 24, 1978; see Fig. 3-24) indicated that the concentration offshore at 3 m depth was 36 ppb (Table 3-8). At the shoals in the mouth of the estuary the concentration rose dramatically to 250 ppb, probably reflecting the physical entrainment and downward movement of surface oil by the violent wave action in the shoals. Inside the shoal area, the concentration was reduced to 140 ppb, with further reduction to 26 ppb at the bridge near Paludenn.

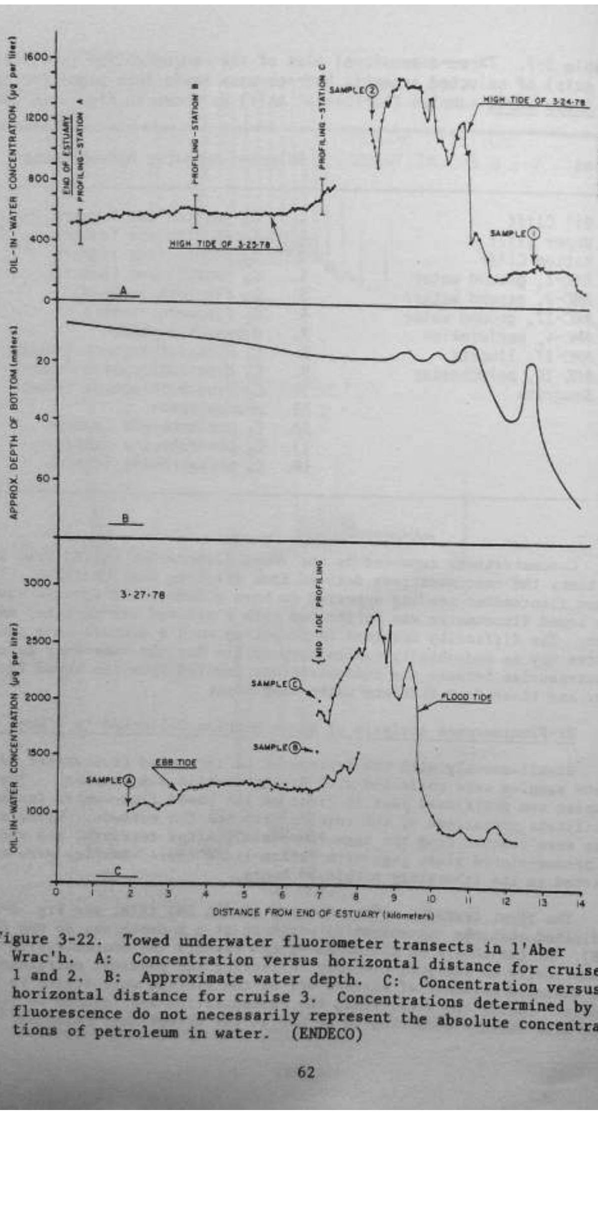


Figure 3-22. Towed underwater fluorometer transects in l'Aber Wrac'h. A: Concentration versus horizontal distance for cruises 1 and 2. B: Approximate water depth. C: Concentration versus horizontal distance for cruise 3. Concentrations determined by fluorescence do not necessarily represent the absolute concentrations of petroleum in water. (ENDECO)

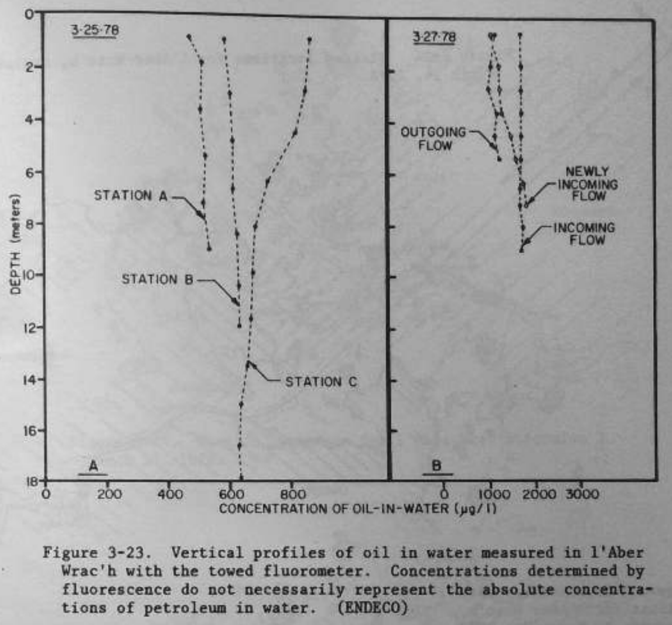


Figure 3-23. Vertical profiles of oil in water measured in l'Aber Wrac'h with the towed fluorometer. Concentrations determined by fluorescence do not necessarily represent the absolute concentrations of petroleum in water. (ENDECO)

The second cruise (March 25, Fig. 3-25) resulted in depth profiles in the shoal area and upstream, based on data from the in-situ fluorometer with discrete water samples collected near surface and near bottom. Near-surface concentrations both upstream and in the shoal area were similar to those of the previous day (Table 3-8). Near-bottom concentrations were higher than near the surface, particularly in the upstream sample. Turbulence is again suspected as the cause for elevated concentrations in the shoal area.

During the third cruise (March 27, Fig. 3-26) depth profiles in the shoal area over a tidal cycle and an offshore and upstream sample were

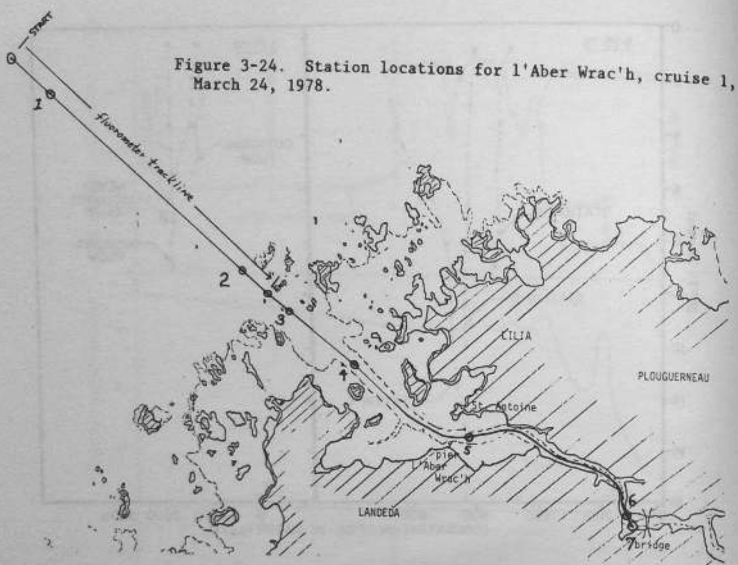


Figure 3-24. Station locations for l'Aber Wrac'h, cruise 1, March 24, 1978.

Figure 3-25. Station locations for l'Aber Wrac'h, cruise 2, March 25, 1978.

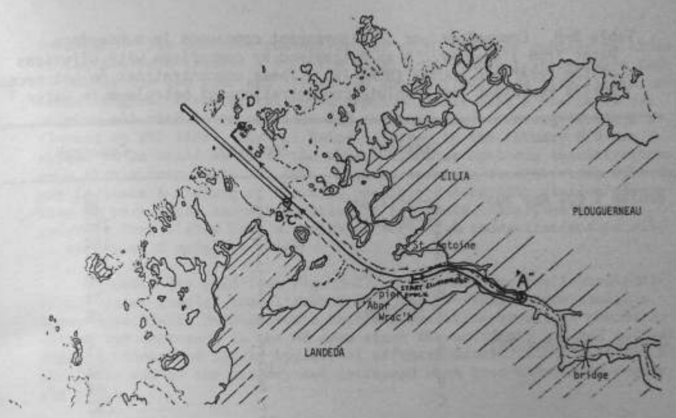


Figure 3-26. Station locations for l'Aber Wrac'h, cruise 3, March 27, 1978.

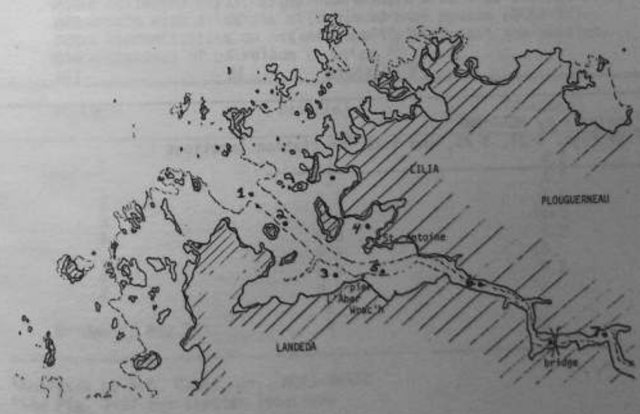


Figure 3-27. Station locations for l'Aber Wrac'h, cruise 4, May 3, 1978.

Table 3-8. Concentrations of fluorescent compounds in subsurface water from l'Aber Wrac'h as determined by comparison with dilutions of the reference mousse (NOAA-16). These concentrations do not necessarily represent the absolute concentrations of petroleum in water.[1]

	Station[2]	Depth(m)	Conc(ppb)
Cruise 1 (24 Mar 78)	1--offshore	3	36
	2--shoals	3	250
	3	3	140
	4	1	110
	5	1	80
	6	1	33
	7--bridge	1	26
Cruise 2 (25 Mar 78)	A	2	57
		10	103
	B	2	59
	C	2	290
		10	330
Cruise 3 (27 Mar 78)	A upstream	1	50
	B (ebb tide)	2	73
		7	69
	C (tide turning to flood)	1	175
		10	250
	C (flood tide)	1	255
		7	340
	D offshore	15	130

[1]Analysis by NOAA-NAF
[2]See Figs. 3-24, 3-25, and 3-26 for station locations

collected. The upstream concentrations of 50 ppb were similar to those of the previous cruises. Near the shoal area, concentrations were near 70 ppb on the ebb tide and 175 to 340 ppb on flood tide with, again, evidence of greater concentration at depth. L'Aber Wrac'h was still receiving oil with incoming tides and this oil was not being completely flushed on ebb tide. The oil being retained in the estuary did not appear to be building up in the water column as upstream concentrations were stable near 50 to 100 ppb. The increases in concentration with depth may indicate a sinking of the oil, possibly due to flocculation/adsorption on particles, and accumulation in sediments. Analyses of one sediment from l'Aber Wrac'h indicated very high concentrations of oil, in excess of 2 mg/g dry weight.

In early May 1978 (see Fig. 3-27), NOAA personnel collected additional water samples from l'Aber Wrac'h for UV-fluorescence analysis. These data (Table 3-9) indicate that concentration of oil in the water column had decreased in the 48 days since the accident, but had not yet reached background levels typical of offshore water. Concentrations at the upper end of the estuary had decreased much less than those nearer the mouth.

Table 3-9. Concentrations of fluorescent compounds in subsurface water collected May 3, 1978, from l'Aber Wrac'h as determined by comparison with dilutions of the reference mousse (NOAA-16). These concentrations do not necessarily represent the absolute concentrations of petroleum in water.[1]

Station[2]	Depth(m)	Conc(ppb)
1	1	4.2
	3	3.8
2	0.5	6.5
3	0.5	lost
4	0.5	9.2
5	0.5	15
6	0.5	9.7
7	0.5	19
	2	22
Bridge (7 May 78)	1	75

[1]Analysis by R.C. Clark, Jr., NOAA-NWAFC
[2]See Fig. 3-27 for station locations

Gas chromatograms of hydrocarbons extracted from water taken near the shoal area were similar to chromatograms of the reference mousse (Figs. 3-5, 3-28, 3-29). Alkanes from n-C_{10} to n-C_{30}, pristane, phytane, and many other less prominent branched/cyclic and aromatic hydrocarbons were detected in the water samples. As would be expected some weathering was apparent, particularly the loss of volatiles. In the unfractionated reference mousse sample, n-C_{11} was the most abundant normal alkane. In the water, n-C_{17} was usually the most abundant. Microbial degradation removes normal (straight-chain) alkanes in preference to branched alkanes, such as pristane and phytane. In the unfractionated reference mousse, the n-C_{17}/pristane and n-C_{18}/phytane ratios were between 2 and 3, while in water samples the ratios were 1 or less, indicating the possibility of microbial degradation of middle-molecular-weight n-alkanes. The peaks in the region of the mono-, di-, and trimethyl naphthalenes were also enriched compared to the normal alkanes in the water samples, consistent with their greater water solubility and greater resistance to degradation. Samples taken in the shoal area on all three cruises were similar, but displayed varying amounts of weathering because fresh oil was still being released from the wreck during the sampling period.

Water samples taken upstream of the shoal area contained a much lower GC pattern of hydrocarbons, but were obviously more contaminated than any offshore station except that near the wreck site (Fig. 3-30).

Analysis of Oil in Subsurface Water Off the North Coast of Brittany

From March 30 to April 4, 1978, the French research vessel Le Suroit (Southwest Wind) occupied 46 stations (Plate 3-2, Fig. 3-31). French scientists conducted extensive sampling for measurements of subsurface oil in water, as well as for standard chemical and biological parameters (Plates 3-3 and 3-4). At the invitation of Dr. Michel Marchand of the Centre Oceanologique de Bretagne, NOAA personnel participated in the cruise. At nine of these stations, near-surface and near-bottom samples were collected with the Niskin sterile bag sampler (Plate 3-5). Samples were transferred immediately upon retrieval to hexane-washed glass jugs with Teflon-lined caps. Extraction of the water with hexane was performed upon return to the shore laboratory. The extracts were analyzed by both UV-fluorescence and glass capillary gas chromatography.

This cruise was conducted two weeks after the wreck occurred and several days after the bulk of the oil had leaked from the ship. Thus, the concentrations reported here may not represent the maximum values attained at the height of the spill. Background values are taken as 0 to 2 ppb as determined by UV-fluorescence on water from station 16 (Table 3-10).

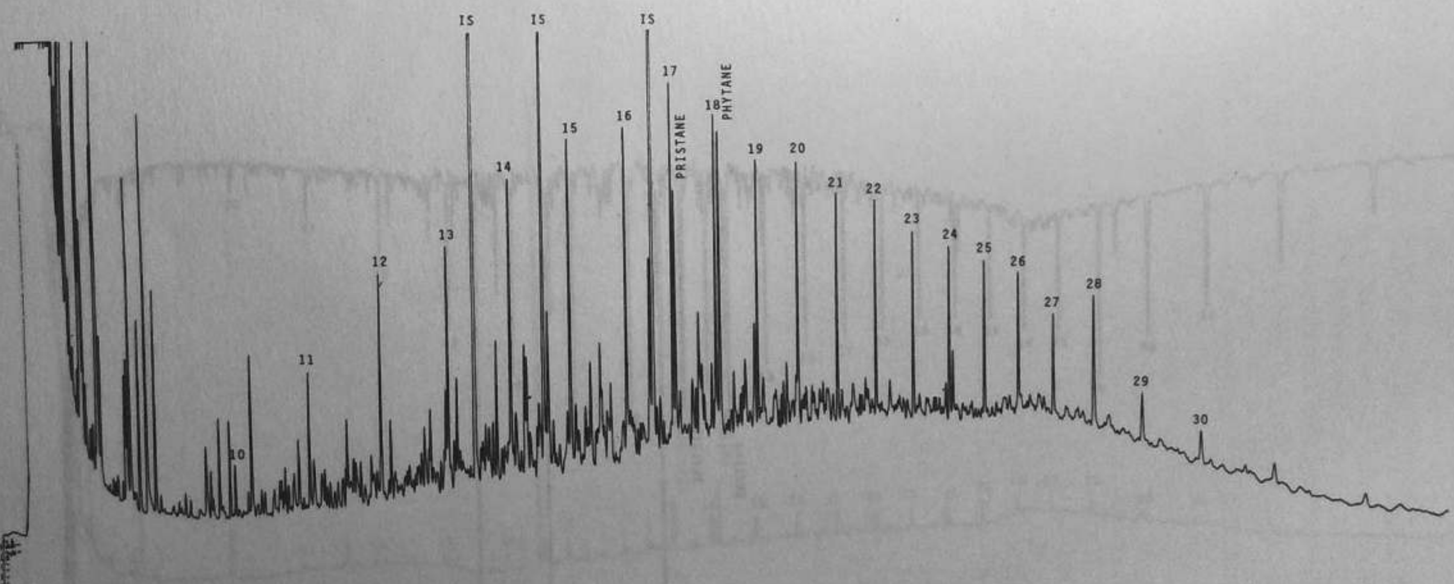


Figure 3-28. High-resolution gas chromatogram of n-hexane extract of water from l'Aber Wrac'h, station C, cruise 2. Numbers refer to n-alkanes of corresponding chain length. Internal standards marked IS. (NOAA-NAF)

70

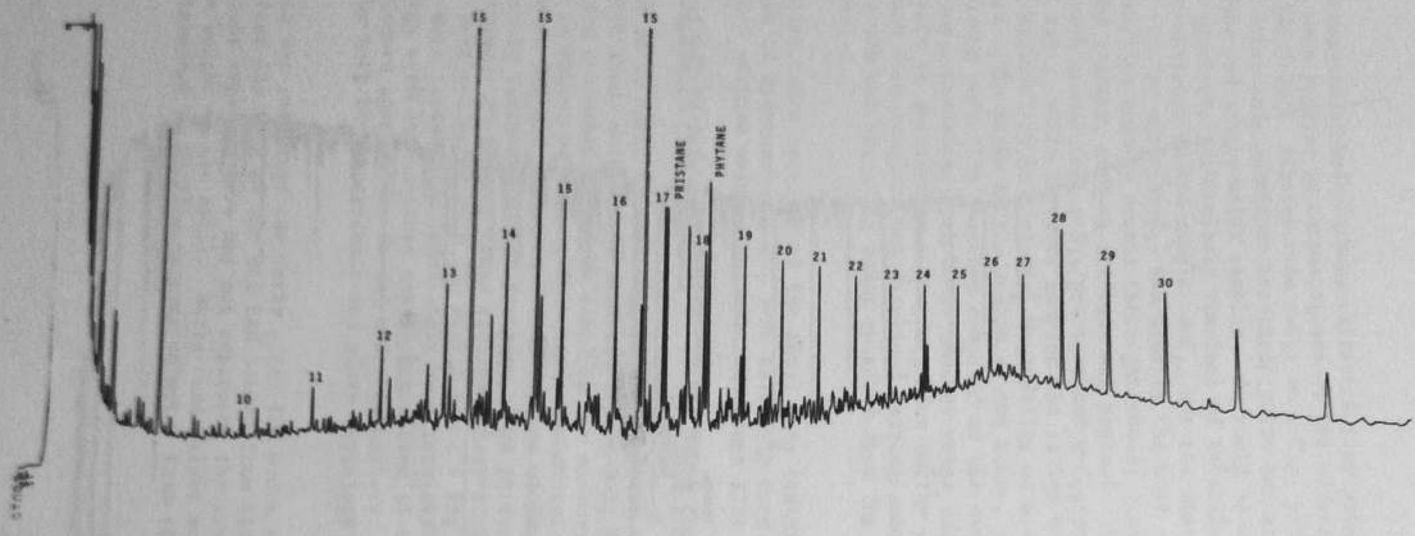


Figure 3-29. High-resolution gas chromatogram of n-hexane extract of water from l'Aber Wrac'h, station C, cruise 3. See legend, Fig. 3-28. (NOAA-NAF)

71

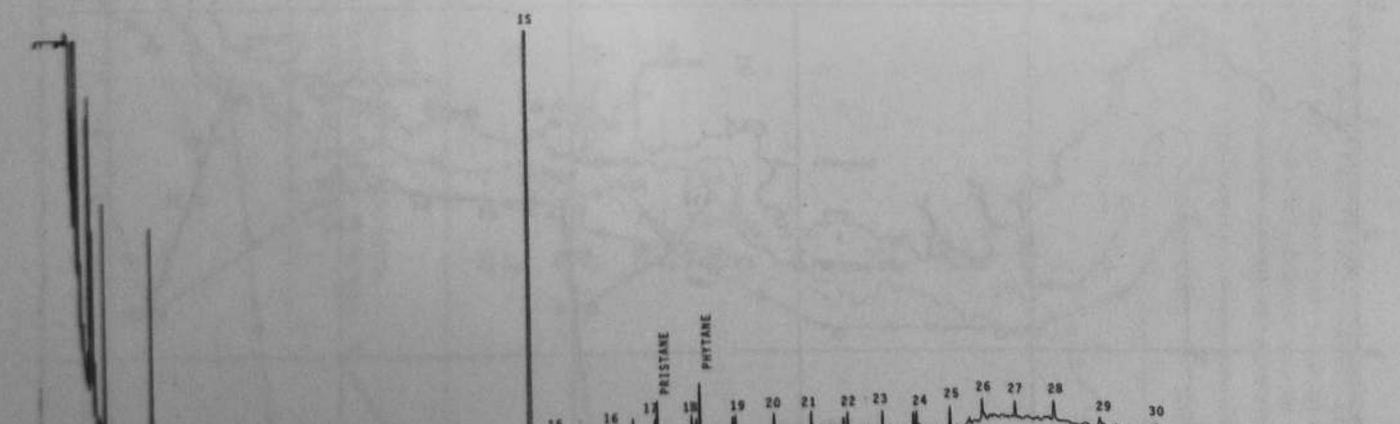


Figure 3-30. High-resolution gas chromatogram of n-hexane extract of water from l'Aber Wrac'h, station B, cruise 3. See legend, Fig. 3-28. (NOAA-NAF)

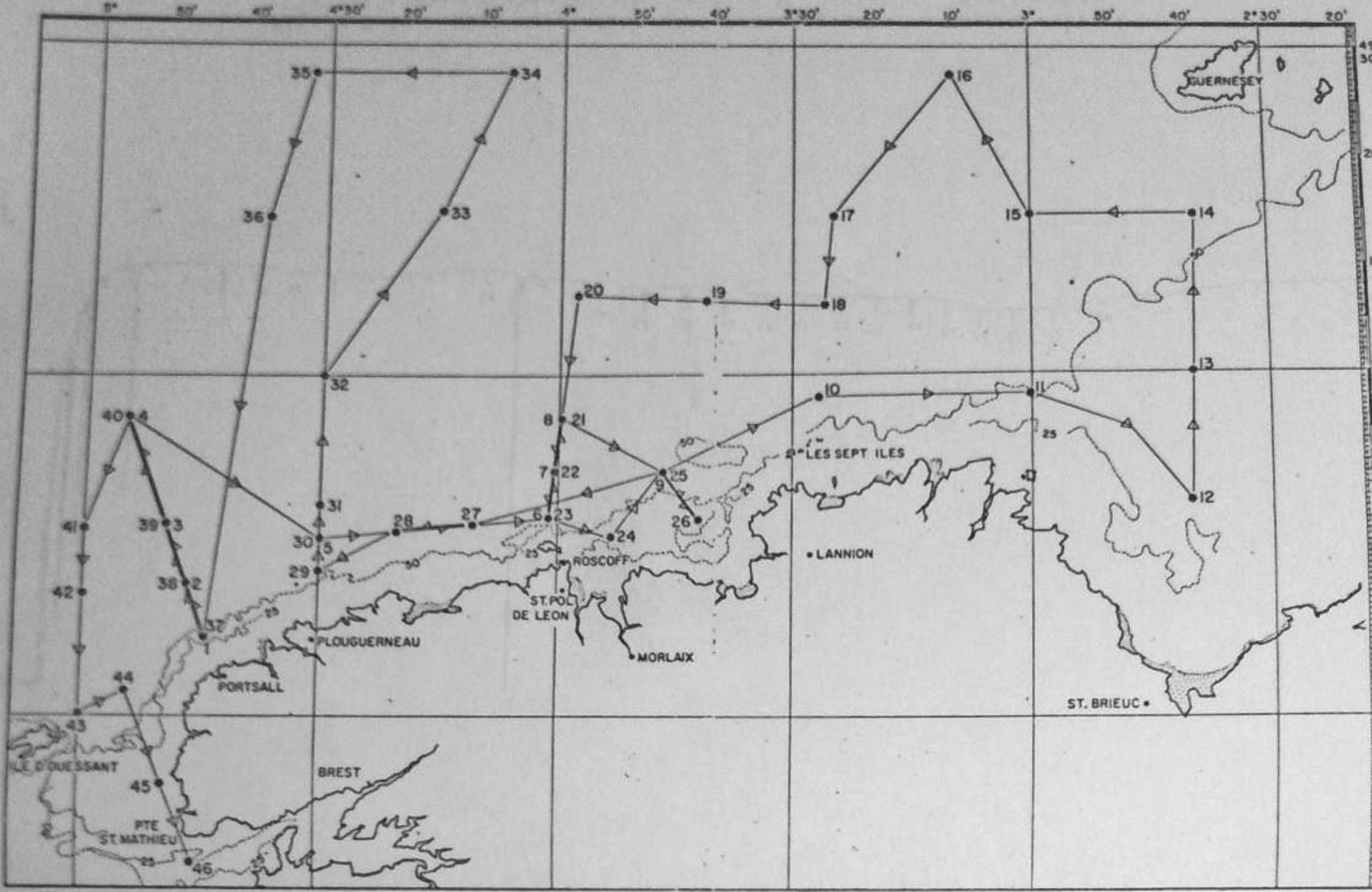


Figure 3-31. Map of stations occupied by the ship Le Suroit to collect water samples from March 30 to April 4.

Table 3-10. Concentrations of fluorescent compounds in offshore waters as determined by comparison with dilutions of the reference mousse (NOAA-16). These concentrations do not necessarily represent the absolute concentrations of petroleum in water.[1]

Station[2]	Depth(m)	Conc(ppb)[3]
1	2	90
3	2	21
	100	26
6	2	40
	40	48
7	2	1.5
	20	12
9	2	3.4
	70	16
16	2	0
	60	2.1
29	2	9.1
	60	140
37	2	1.5
	90	0.1
39	2	0.8
	90	1.7

[1]Analysis by NOAA-NAF
[2]See Fig. 3-31 for station locations
[3]Average of duplicate analysis--average deviation about the mean = ± 20%

Surface mousse, slick, or globular oil, was present at stations 1, 3, 6, and 29. These stations also showed high concentrations of oil (9 to 90 ppb by UVF) at 2 m depth. Surface oil was absent at the other stations and the concentration at the 2 m depth was lower (0 to 3 ppb by UVF), essentially at background levels. Stations 1 and 3 were reoccupied as stations 37 and 39 near the end of the cruise (April 3). Concentrations observed at this later time were near background levels. All oil had leaked from the ship by this time and the water column did not contain residual hydrocarbons.

Except at station 1 (37), near-bottom samples contained greater hydrocarbon concentrations than at 2 m depth, even when floating oil was observed at the surface. The highest offshore concentration was 140 ppb at 65 m depth at station 29. The role of dispersants and sinking agents used to counteract the oil spill must be clarified with regard to the observed increase in hydrocarbon concentration with depth.

Gas chromatographic data reflect the relative UV-fluorescence data. The chromatogram of station 1, 2 m (90 ppb) contains n-C_{12} to n-C_{32} n-alkanes, pristane, and phytane (Fig. 3-32). At station 9, the 2 m sample (3.4 ppb) contains nothing that can be attributed to the oil (Fig. 3-33) while the 70 m sample (16 ppb) has elevated concentrations of a few peaks which bear a resemblance to the station 1 sample.

Analysis of Oil in Interstitial Water from Beaches

Interstitial and ground water samples were obtained by digging a hole in the beach, placing a closed sampling container in the hole, allowing the hole to fill with water, and opening the sampling container. The cap of the container was then replaced before the container and sample were withdrawn. Fig. 3-18 shows a three-dimensional plot of the concentration of selected aromatics in samples of ground water obtained from AMC-1, AMC-3, and AMC-17. Almost no aromatics were found in these samples. Table 3-11 lists the concentrations found in interstitial water samples and in surf samples obtained at EPA-4 and EPA-5 on March 27, 1978. The chromatograms of the samples from the interstitial water and the surf were quite similar at EPA-4. The chromatograms from interstitial and surf water samples from EPA-5 showed some differences (Fig. 3-34), but the presence of oil was evident.

The finding of petroleum hydrocarbons in interstitial water at the EPA sample sites contrasts with the absence of oil aromatics in ground water samples analyzed by UNO-CBS. This discrepancy may be explained by differences in sample locations, sample size, or detection limits of analytical instrumentation, but is believed to result from differences in the types of water sampled. The EPA samples were taken within 30 meters of the shoreward limit of the surf zone and represented interstitial water at that location. The UNO-CBS samples were obtained in areas higher on the beach and probably represented an input from ground water from natural aquifers.

75

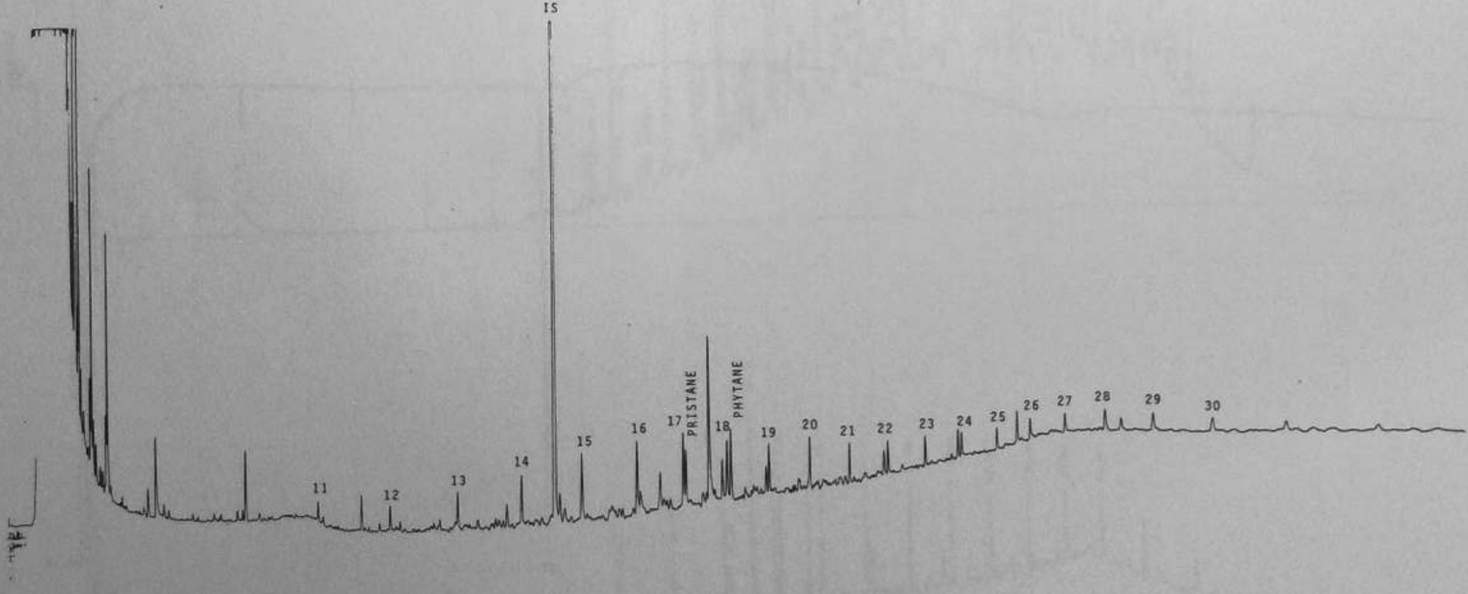


Figure 3-32. Gas chromatogram of a hexane extract of seawater from Station 1, 2 m. See legend, Fig. 3-28. (NOAA-NAF)

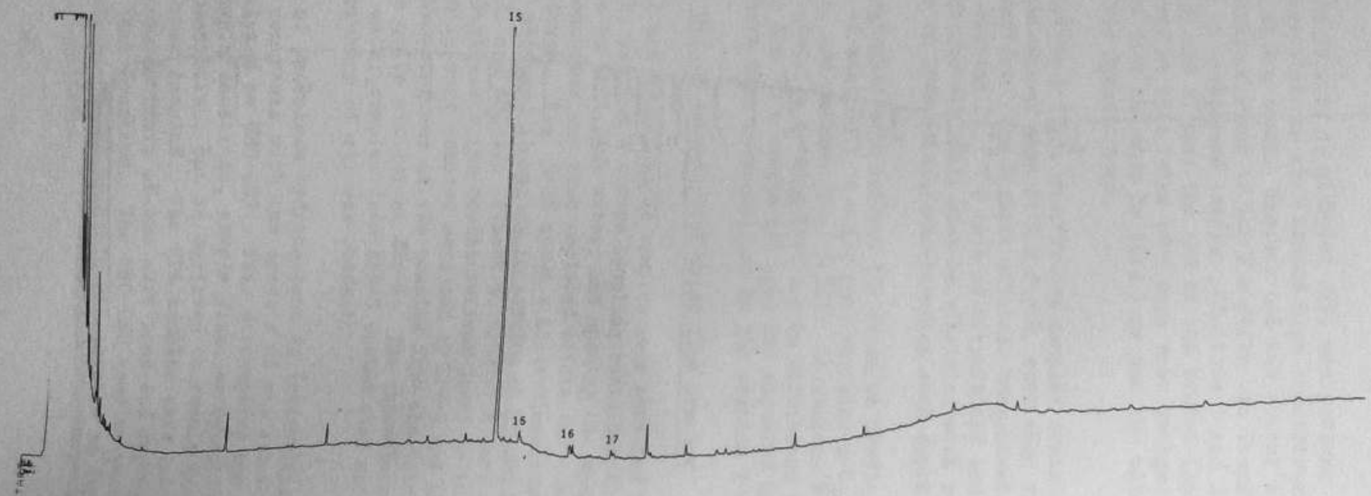


Figure 3-33. Gas chromatogram of a hexane extract of seawater from Station 9, 2 m. See legend, Fig. 3-28. (NOAA-NAF)

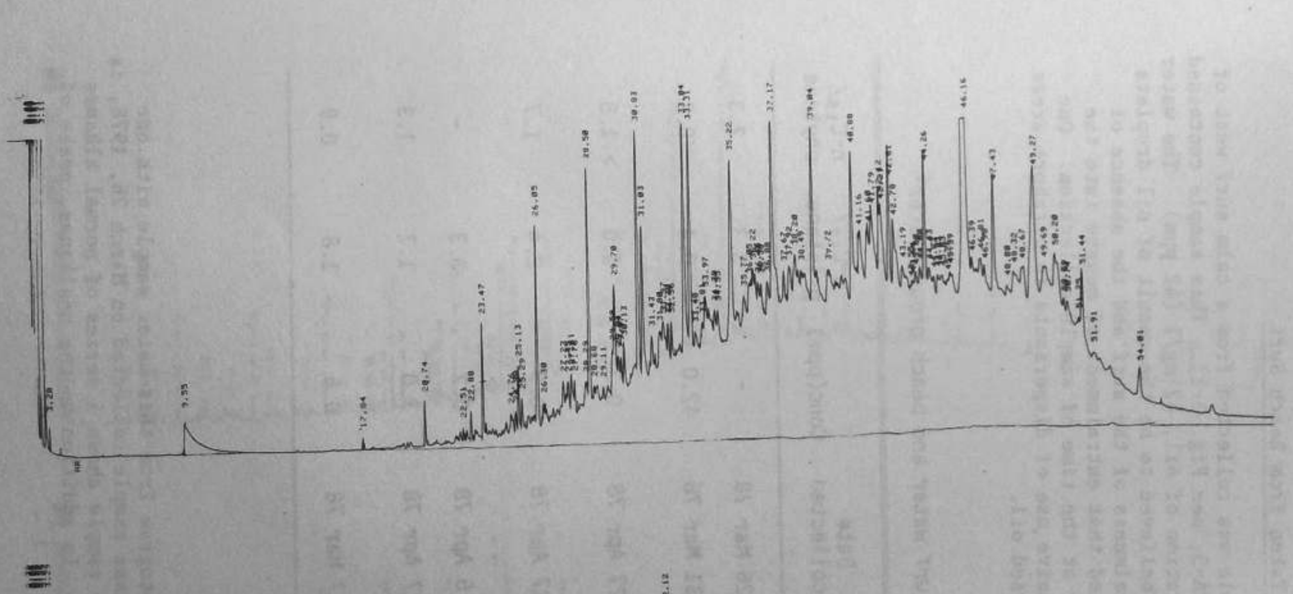


Figure 3-34. Gas chromatograms of interstitial water (upper trace) and surf water (lower trace). Samples taken at EPA-5 (St. Efflam) on April 27, 1978. (EPA-ERLN)

Analysis of Oil in Water Taken from Beach Surf

One subsurface water sample was collected from a calm surf west of the mouth of l'Aber Benoit (EPA-3, see Fig. 3-1). This sample contained an exceptionally high concentration of oil, 42 mg/l (42 ppm). The water itself had a brown coloration believed to be the result of oil droplets dispersed in the water. The calmness of the surf and the absence of visible surface mousse indicated that entrainment of mousse into the water column was not occurring at the time of sample collection. One could speculate that the extensive use of dispersants in offshore areas resulted in this finely dispersed oil.

Table 3-11. Oil in surf water and beach ground water[1]

Station	Description	Date collected	Conc(ppm)	$n-C_{17}$/ pristane	$n-C_{18}$/ phytane
NOAA-16	Reference mousse	26 Mar 78	-	3.3	2.3
EPA-3	Subsurface water from surf zone	31 Mar 78	42.0	0.4	0.3
EPA-4	Locquirec, interstitial water	27 Apr 78	0.3	3.0	> 1.8
EPA-4	Locquirec, surf water	27 Apr 78	0.9	2.4	1.7
EPA-4	Locquirec, tide	6 Apr 78	0.2	3.3	-
EPA-5	St. Efflam, interstitial water	27 Apr 78	3.0	1.7	1.3
EPA-5	St. Efflam, surf	17 Mar 78	0.6	1.8	0.9

[1]Analysis by EPA-ERLN

A comparison of the chromatogram from this water sample with one obtained from the reference mousse sample collected on March 26, 1978, is shown in Fig. 3-35. The mousse sample shows a series of normal alkanes (n-alkanes) from $n-C_8$ to $n-C_{30}$. In addition to the n-alkanes, peaks of

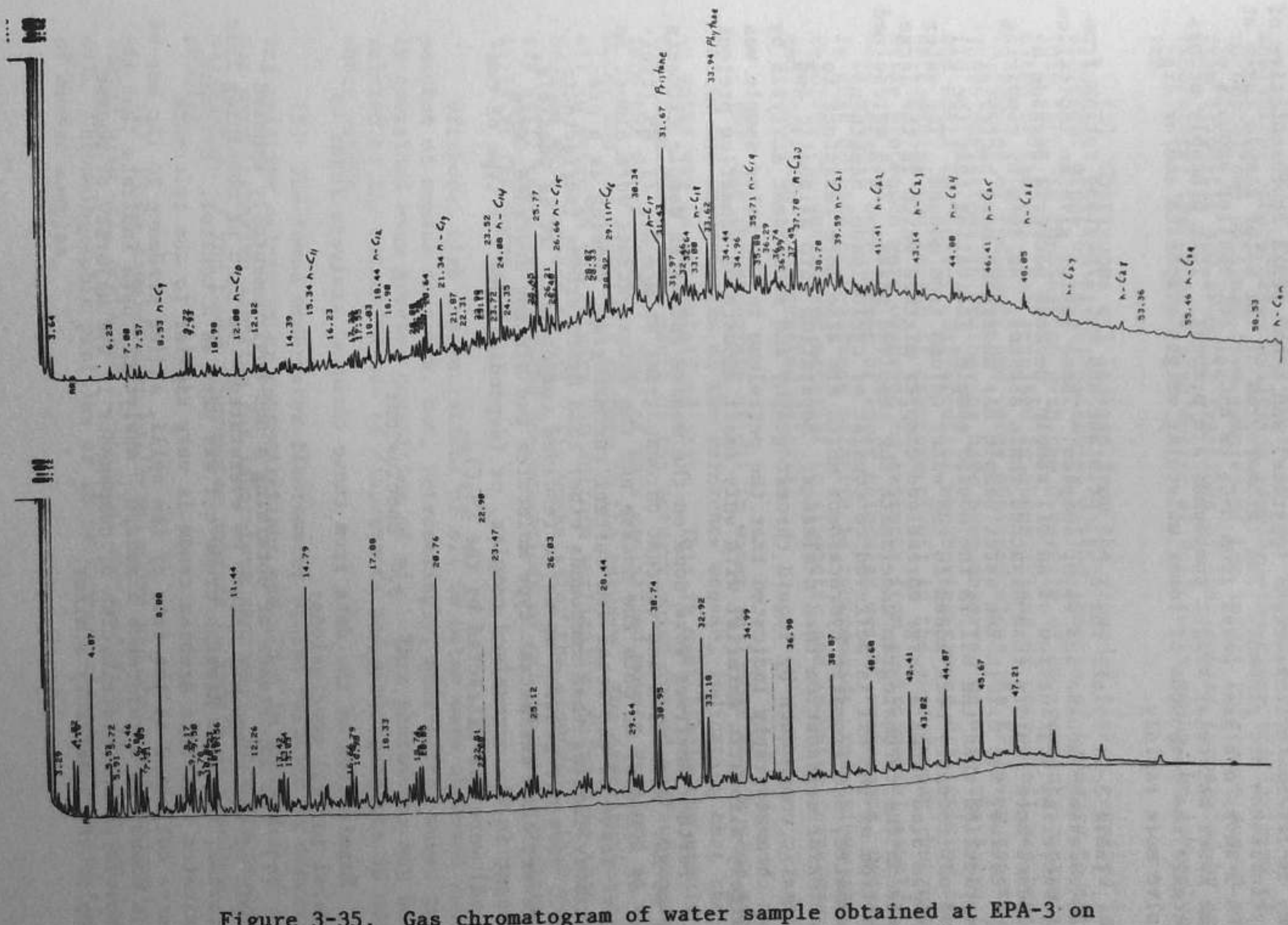


Figure 3-35. Gas chromatogram of water sample obtained at EPA-3 on March 31, 1978 (upper trace). Gas chromatogram of reference mousse obtained near wreck on March 26, 1978 (lower trace). (EPA-ERLN)

the isoprenoids 2, 6, 10, 14-Tetramethylpentadecane (pristane) and 2, 6, 10, 14-Tetramethylhexadecane (phytane) and other peaks representative of cycloalkanes are present. The chromatogram of the water sample taken at EPA-3 shows n-alkane peaks from n-C_9 to n-C_{30}, but smaller amounts of the lower molecular weight compounds are present. This probably occurs because the compounds of lower molecular weight evaporate and/or dissolve more rapidly.

Table 3-11 lists the n-C_{17}/pristane and n-C_{18}/phytane ratios from the reference mousse and water samples. These ratios give an indication of bacterial degradation of an oil sample, because bacteria degrade n-alkanes more rapidly than branched chain alkanes. As seen by comparing the ratios, the oil in the water sample has undergone more bacterial degradation than the oil in the mousse sample, indicating that the oil had not recently been added to the water column from mousse. The water sample also shows a large unresolved complex mixture which is the large area on the chromatogram underneath the resolved peaks. This unresolved portion of the oil is believed to consist of cycloalkane, naphtheno-aromatic, and aromatic hydrocarbons which are also more resistant to bacterial degradation than n-alkanes. Separation into aliphatic and aromatic components by liquid chromatography and subsequent analysis by gas chromatography indicated that the petroleum in the water sample was largely aliphatic material with only small amounts of aromatics present.

Further analyses were done on the mousse and water sample extracts by GC-MS. Extracted ion current chromatograms at m/e 57, 71, 85 (typical of alkanes) on both the mousse and the water extract were almost an exact trace of the total ion current chromatogram, showing as a preliminary finding that compounds other than hydrocarbons (surfactants, etc.) were not present as major resolved components. It is possible, however, that surfactant type molecules had already degraded, were present in the unresolved complex, or (depending upon the type of compound) were not extracted by the CH_2Cl_2.

3.4 Conclusions

Examination of the data from these chemical analyses leads to several initial conclusions:

(1) The importance of obtaining a non-environmentally exposed sample of the cargo oil cannot be overstated. In lieu of obtaining this material, a medium Arabian crude oil was used as a control. Evidence indicates that this Arabian crude is very similar to the reference mousse collected at the site of the spill, adding credence to the use of this mousse as a reference standard. Analytical data indicate that the composition and distribution of components in the majority of mousse samples are remarkably similar.

(2) While minor differences in methodology existed among the three analytical laboratories analyzing samples, the close similarities of gas chromatograms obtained from samples of the intact reference mousse and from aliphatic and aromatic fractions of that mousse (separated by each laboratory) indicated a high degree of uniformity among the laboratories.

(3) Continuous oil leakage from the grounded tanker resulted in different areas of coastline having varied lengths of exposure to oil. This fact, in combination with the diversity of environments contaminated by the oil, has resulted in observations of uneven oil weathering in samples of sediments and water obtained along the Brittany coast. These variations in weathering have been observed on both the large (km) and small (m) scale. Differential weathering caused difficulties in determining the length of exposure of oil in the environment, but weathering processes were observed in extracts from environmental samples. Most notable were losses of lower molecular weight components, decreases in peak heights of n-alkanes relative to isoprenoids, reductions in resolved vs. unresolved material in aliphatic and aromatic fractions, and increases in oxygenated material.

(4) Gas chromatograms of oil in water in l'Aber Wrac'h were similar to the chromatogram of the reference mousse, indicating that the oil in water was in an emulsified state. This is most likely the result of the turbulence at the mouth of the estuary which forced surface mousse into the water column. Some of this emulsified mousse remained in the water and was detectable further up the estuary. The distribution of oil in water in the estuary was uniform vertically, indicating that the benthos were exposed to oil. Six weeks after the grounding, this estuary still contained elevated concentrations of oil in water, particularly at the upper end.

Offshore, high concentrations of oil in water were observed under patches of mousse or slick, but, interestingly, near-bottom water usually contained even greater quantities of oil. This phenomenon may be related to the extensive use of dispersants and sinking agents in offshore waters.

(5) The towed underwater fluorometer proved valuable in determining relative oil-in-water concentrations and aided in selection of sites for more intensive sampling for laboratory analysis. Accurate field calibration of the towed fluorometer appears to remain an unsolved problem.

(6) Biota samples were collected alive and while not obviously coated with oil, contained substantial contamination from the spilled oil. Chromatographic profiles of these samples closely resembled those of mousse samples.

(7) A careful analysis of mass spectrometric data indicates the presence of photo-oxidation products of dibenzothiophene and its alkyl homologs. There was no mass spectral evidence for photo-oxidation products of the naphthalenes and phenanthrenes. Further, it should be pointed out that evidence for the photo-oxidation of mousse is found in the complex unresolved chromatographic mixture (hump) in the methanol fractions in laboratory-photolyzed and environmental mousse samples. Volatile oxygenated molecules were tentatively identified in the head-space over a mousse sample, presumably produced by microbial metabolism within the mousse.

(8) It is obvious that further studies of weathering, including bio- and photo-oxidation, of spilled oil are needed. These studies will require special sampling and analytical techniques since many of the primary oxidation products of petroleum aromatic compounds are labile.

(9) Selected field sites should be resampled for hydrocarbon present in the water column, at the air-sea interface, in the biota, and in sediments at regular intervals for a period of time sufficient to trace the loss of oil from the environment and the subsequent accumulation of oil-related products.

3.5 Acknowledgments

Many individuals and organizations contributed substantially to the contents of this chapter. The field chemistry program was supported by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) of NOAA with funds derived from the Department of Interior Bureau of Land Management (BLM). Laboratory analyses were supported by an additional funding from BLM to NOAA. Ship time was provided by CNEXO-COB.

The laboratories providing sample analysis are to be commended for their rapid response and the high quality of their work. In particular, the authors acknowledge the following:

UNO-CBS. Dr. Edward B. Overton and Dr. Jayanti R. Patel, project managers; Doug Carlisle, Chris Raschke, MaryAnn Maberry, Robert Bowles, Dianne Adamkiewicz, Chuck Steele, Jo Ann McFall, Wayne Mascarella, for help in analyzing the samples; and Diane Trembley and Michelle Aguiluz for preparing the manuscript.

EPA-ERLN. Mr. Curt Norwood of ERL-N, Mr. Randy Dimock, Mr. Robert Bowen, and Dr. Eva Hoffman of University of Rhode Island Graduate School of Oceanography, for their valued assistance in preparing and analyzing samples.

NOAA-NAF. Dr. William D. MacLeod (Manager), Donald W. Brown (Assistant Manager), Scott Ramos, Russell Dills, Don Dungan, Andrew Friedman, and Terry Scherman.

NOAA-NWAFC. Robert C. Clark, Jr.

ENDECO. William Williams, Dr. Ed Brainard, and Dr. William Kerfoot.

Special thanks to Lt. John J. Kineman (NOAA Corps--OCSEAP) for providing field logistics and managing the towed fluorometer program, and to Dr. Michel Marchand of COB for providing laboratory space, equipment, and supplies and most importantly his understanding and friendship.

finally, sheltered rocky coasts (no. 8), sheltered tidal flats (no. 9), and estuarine marsh systems (no. 10) once again proved to be the most vulnerable of all coastal environments to oil spill damage. These observations provide encouragement and incentive to continue to apply the vulnerability index to areas in the U.S. threatened by potential oil spills. The Brittany coastline is particularly analogous to the coastline of Maine and parts of southern Alaska.

During the first week after the grounding, oil on tidal flat and beach surfaces lifted off the bottom with each incoming tide. However, one month later, a large patch of oil mixed with sediment was found on the tidal flat surface at Portsall, and many beaches retained oil during the flooding tide. In these cases, oil became sediment-bound and remained on the bottom. The physical mixing of oil with sediment to form a denser-than-water mixture provides a possible mechanism for causing oil from the Amoco Cadiz to sink to the bottom.

Although the surfaces of the beaches and tidal flats at many places were free of oil, the interstitial ground water was contaminated. This may have been the cause of the extensive biological kills at certain areas. Unfortunately, the use of large pits and trenches as collection sites for the oil may increase the amount of ground water contamination.

The use of bulldozers to plow heavily oiled gravel into the surf zone for cleansing by wave action is a sound practice, from a geological point of view because no sediment is removed from the beach. Removal of sediment from certain areas increased the rate of beach erosion. The unrestricted use of heavy machinery on the beach and low-tide terrace generally turned oil deeper into the sediments. Where possible, traffic should be limited to specified access routes.

4. INVESTIGATIONS OF BEACH PROCESSES

Erich R. Gundlach* and Miles O. Hayes*

4.1 Synopsis

According to our best estimate, 64,000 tons of the Amoco Cadiz oil came ashore along 72 km of the shoreline of Brittany during the first few weeks of the spill. A prevailing westerly wind pushed the oil against west-facing headlands and into shoreline embayments as it moved east. A wind reversal in early April moved the oil in the opposite direction, contaminating previously untouched areas and transporting the oil as far southwest as Pointe du Raz (southwest of Brest). At the end of April, the total volume of oil onshore was reduced to 10,000 tons, but, by that time, 320 km of shoreline had been contaminated.

Coastal processes and geomorphology played a major role in the dispersal and accumulation of the oil once it came onshore. For example, oil accumulated at the heads of crenulate bays and on tombolos (sand spits formed in the lee of offshore islands). Local sinks, such as scour pits around boulders, bar troughs (runnels), marsh pools, and joints and crevasses in rocks, tended to trap oil. The grounded mousse was either eroded away, or buried (up to 70 cm) under new sediment deposits, in response to the vagaries of the beach cycle. The details of oil erosion and burial were determined by resurveying 19 permanent beach profiles which were established during the first few days of the spill.

Classification of the coastal environments of the Amoco Cadiz oil spill site according to our oil spill vulnerability index (scale of 1-10 on basis of potential oil spill damage) revealed a good correlation with earlier findings at the Metula and Urquiola oil spill sites. Exposed rocky coasts and wave-cut platforms (index nos. 1 and 2) were cleaned of extremely heavy doses of oil within a few days. Fine-grained sand beaches (no. 3) proved to be easily cleaned, whereas coarse-grained sand beaches (no. 4) showed considerable oil burial in areas where berms were developed. Exposed tidal flats (no. 5) underwent extensive biological damage and experienced potential long-term pollution of the interstitial ground water. (No. 6 was not represented.) Gravel beaches (no. 7) were deeply penetrated by the oil, creating special cleaning problems. And

*Coastal Research Division, Dept. of Geology, U. of South Carolina, Columbia, SC 29208.

4.2 Introduction

The objectives of the work discussed in this chapter are to describe the influence of beach processes and sedimentation on the dispersal, grounding, burial, and long-term fate of the Amoco Cadiz oil. These observations should provide valuable insights for coastal zone managers in the United States concerned with contingency planning for oil spills. This is true especially with regard to understanding the vulnerability of different coastal environments to oil spill impacts, as well as to planning for the availability of equipment and manpower needed for shore protection and clean-up in the event of a major spill.

In order to achieve these objectives, a program of field studies was begun on Sunday, March 19, 1978, three days after the initial wreck of the tanker. In total, 15 days were spent in the field during the first visit. The first field crew consisted of Miles O. Hayes, Erich R. Gundlach, and R. Craig Shipp of the U. of South Carolina (under contract to the Research Planning Institute, Inc. (RPI) of Columbia, South Carolina, U.S.A.). Also, Laurent D'Ozouville of the Centre Oceanologique de Bretagne (COB) participated in several days of field activities. The site was revisited between April 20 and April 28, 1978, by Gundlach and Kenneth Finkelstein of RPI. Dr. D'Ozouville again participated in each day of the field work.

In the field, our work consisted of overflights and intensive ground inspection and surveys of the entire affected area. For purposes of description, the study area is divided into 11 sections. Descriptions of 19 permanent beach survey stations and 147 beach observation stations (Fig. 4-1) are given under the discussion of each of the 11 sections (below). Extensive photography was carried out, with approximately 3,000 photographs being taken on the first trip and approximately 1,200 on the second. Thirty-five representative color photographs that illustrate the beach processes are given in Plates 4-1 through 4-33 (Appendix B).

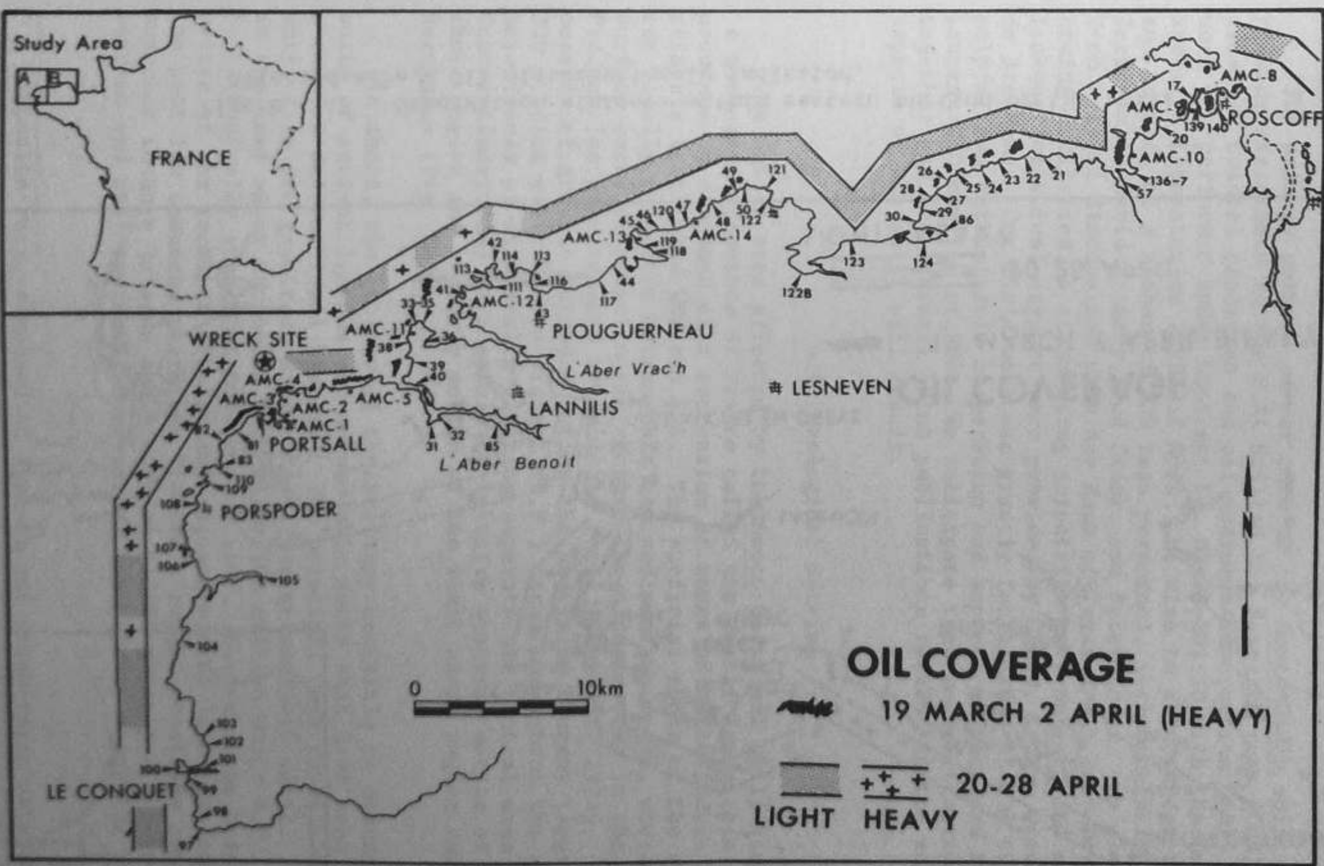


Figure 4-1A. Locations of observation stations within western portion of the spill-affected area. Oil distribution for study periods one (March 19 to April 2) and two (April 20 to 28) are indicated.

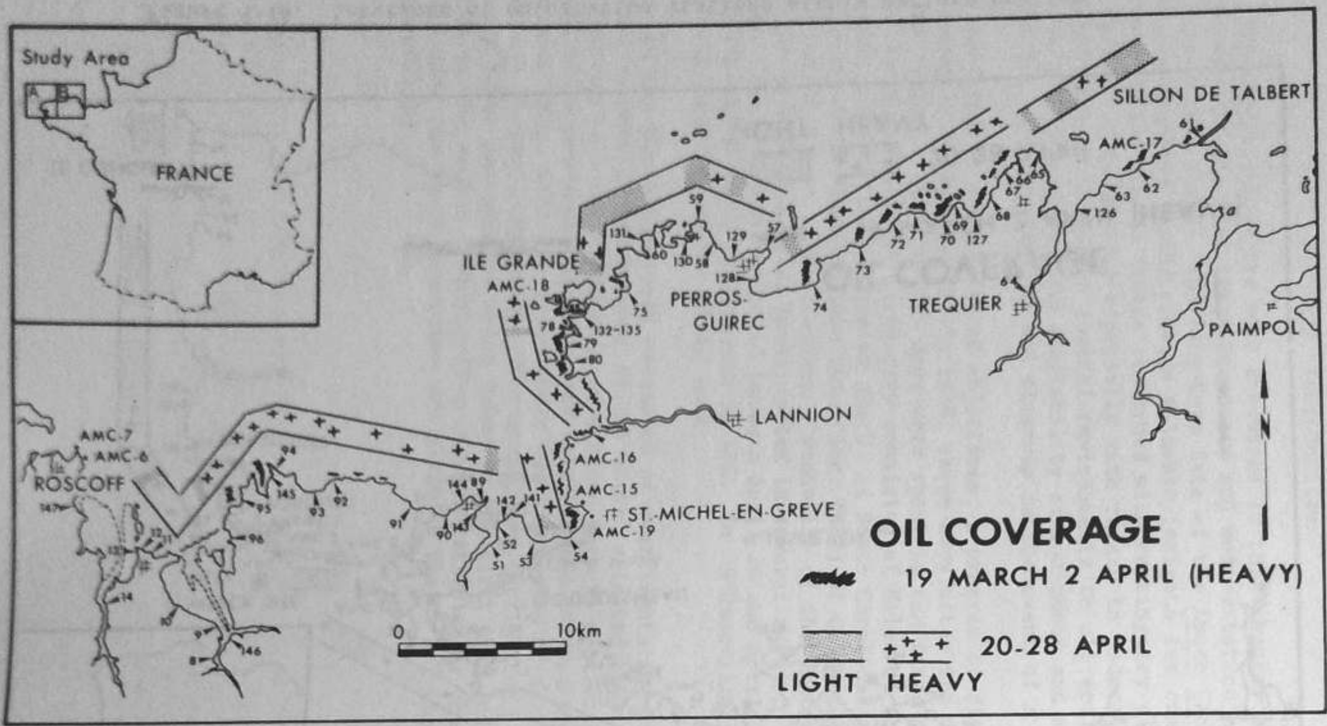


Figure 4-1B. Observation stations within eastern portion of the spill-affected area. Oil distribution is indicated.

4.3 Acknowledgments

The primary purpose of our work on the Amoco Cadiz spill was to provide assistance to the NOAA Spilled Oil Research team (SOR) in the areas of coastal processes and oil-sediment interaction. All of our work was performed under Contract No. 03-78-B01-50 with the Environmental Research Laboratories (ERL) of NOAA. We wish to acknowledge the help and support of a number of SOR team personnel, including Wilmot Hess, Jerry Galt, David Kennedy, Bud Cross, and Peter Grose. We also gained from helpful discussions with Roy Hann of Texas A & M University. Living facilities, a stimulating scientific environment, and miscellaneous logistical support were provided by CNEXO, Centre Oceanologique de Bretagne. Our field work was greatly facilitated at all times by the helpful and enthusiastic cooperation and support we received from Laurent D'Ozouville of COB. We anticipate that we will continue to work together and that several joint publications related to the scientific aspects of the spill will result.

4.4 Geological Setting

The entire area affected by the Amoco Cadiz oil spill lies within a geological province of France called the Massif Armoricain. This province is composed of a succession of zones of anticlinoria and synclinoria that trend WNW and ESE. The surficial rocks of the synclinoria are usually Paleozoic metamorphic and sedimentary rocks, whereas the surface rocks of anticlinoria contain the oldest rocks in the area, Precambrian granites and metamorphic rocks (Debelmas, 1974). Localized massifs of granite intruded during the Hercynian orogeny (approximately 300 million years before present (B.P.) occur throughout the area. Two major zones of strike-slip faulting separate the central area (Domain Centre Armoricain) as a result of relative westerly motion of the north shore region and easterly motion of the south shore region during the Hercynian (Fig. 4-2).

In short, the geology of the Brittany peninsula is dominated by a suite of ancient igneous and metamorphic rocks that have been subject to a complex deformational history. The principal rock types along the oil spill site are granites, migmatites[1], and metamorphic rocks. Inasmuch as the last major tectonism took place 200 million years B.P., the area is tectonically stable at the present time. However, the resistant nature of the rocks to erosion and adjustments of land-sea levels over the past few thousand years has created a rugged coastline composed of numerous inshore islands and erosional cliffs separated by minor pocket beaches and ria[2] systems. Everywhere, the primary shoreline trends are

[1] A composite rock, composed of igneous and metamorphic materials mixed together as a result of intensive igneous and metamorphic action.

[2] Drowned river valley.

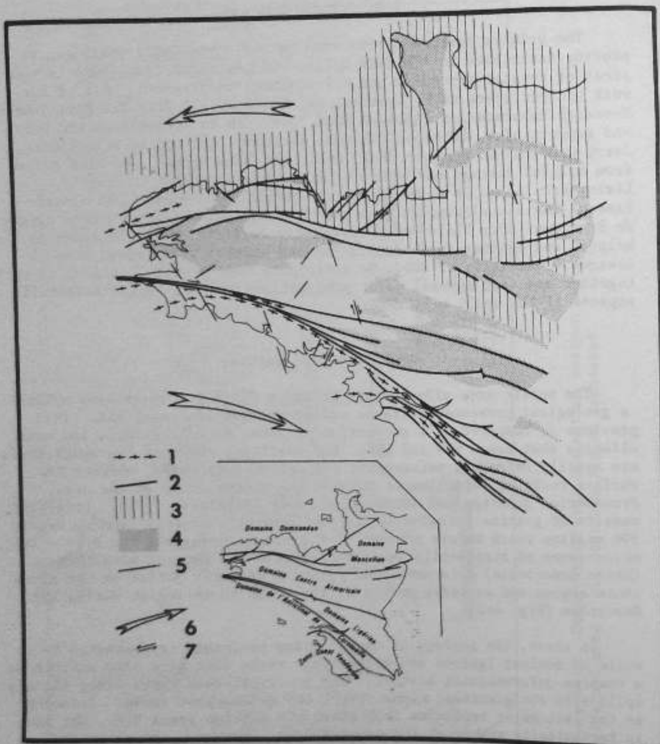


Figure 4-2. Tectonic development of the Massif Armoricain (from Debelmas, 1974); (1) zone of early activation, (2) major shear zones, (3) region of minor activation of Hercynian basement by pre-Cambrian granites, (4) Paleozoic cover sheets and regions of large synclines, (5) post-Stephanian fractures, (6) primary displacement, and (7) secondary displacement.

controlled by bedrock geology, with local trends being controlled by weathering and erosion along structural elements, such as faults, joints, and dikes. An example of this type of control along the coast near St. Malo is illustrated in Figure 4-3.

4.5 Coastal Processes

Information on physical processes of the spill site is discussed by Galt and Grose in Chapter 2. This section is a brief discussion of those physical processes related directly to the beach dynamics and oil grounding.

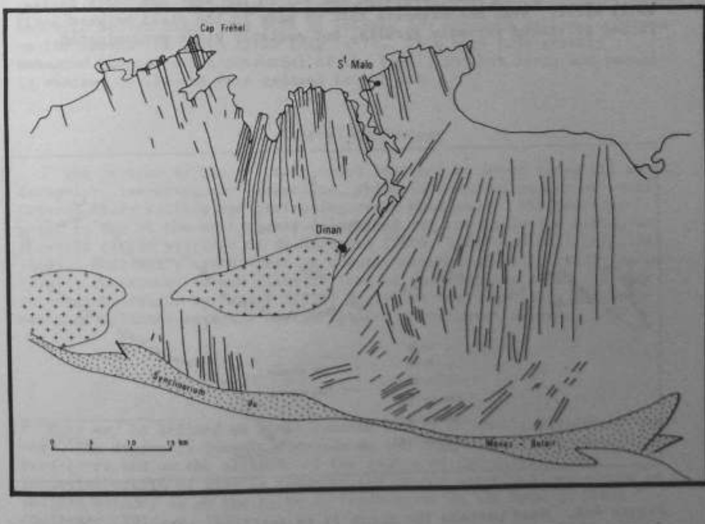


Figure 4-3. Orientation of vein field and jointing pattern of north-central Brittany (from Debelmas, 1974). Note control of structural elements on shoreline configuration.

Our field observations indicate that the spill site is one of intense dynamic coastal processes. These conditions of high wave and tidal energy are generally conducive to rapid natural dispersion of the oil in exposed environments. However, the intricate topography of the shoreline allows for the sheltering of some environments from the waves and currents.

4.5.1 Winds and Waves

Wind patterns played a major role in the dispersal of the Amoco Cadiz oil along the shoreline. Data collected by the French Meteorological Agency (presented in Fig. 4-4) show that the wind blew consistently from the west between March 18 and April 2, the time during which all the oil was lost from the tanker. Winds commonly blew over 20 km/hr throughout this period. This consistent strong, westerly wind accounts for the uniform west-to-east dispersal of oil during late March. The wind changed on April 2 and blew consistently from the northeast until April 10, the date on which our records (from the French Meteorological Agency) end. Presumably, it was these and later northeast winds, aided by tidal currents, that dispersed the oil to the west and south during early April. Wind measurements that we made in the field between April 22 and 26 showed variable results, but easterly winds predominated.

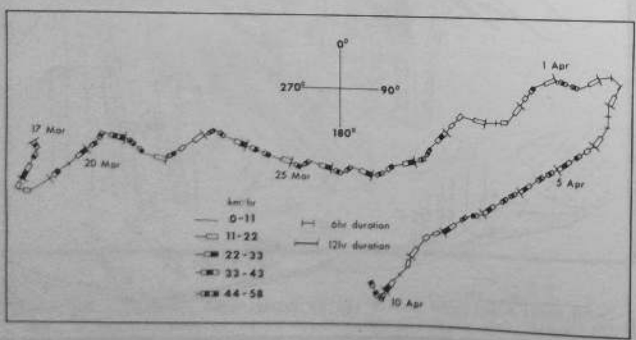


Figure 4-4. Wind pattern for March 17 to April 10, 1978, from the French meteorological station 1 km north of l'Aber Wrac'h. The wind shift on April 2 caused the oiling of previously clean coastal areas south of the wreck site.

Large waves were observed at high tide throughout the first field study period (March 19 to April 3). Estimates of significant wave heights were consistently on the order of 1 to 1.5 m, with heights of 2 m being common during the first few days of the spill. On the other hand, waves observed during the second field visit in late April were quite small, rarely exceeding 15 cm (at low tide). Unfortunately, no precise wave measurements (i.e., wave gauge recordings) were made during the spill to our knowledge.

4.5.2 Tides and Tidal Currents

The mean tidal range at Morlaix, which is centrally located in the spill site, is on the order of 6 to 7 m (Fig. 4-5). These large tides generated strong tidal currents throughout the spill site. The tidal current variability for the area is illustrated by the graphs in Figure 4-6. Our team measured (with floats) tidal currents of 1.4 m/sec in the channel north of Roscoff. From the air, streaming lineations of mousse and other floating debris around stationary objects (e.g., rocks and buoys) gave evidence of the strong tidal currents. An exceptional spring tide of 8.1 m, which was caused by a combination of spring tides and wind set-up associated with an intense low pressure system, occurred on the weekend of March 25-26 (Fig. 4-7). This high tide greatly enhanced the pollution potential of the spill, in that areas not normally reached by the sea were exposed to the oil.

4.6 Coastal Morphology

The portion of the Brittany coast impacted by Amoco Cadiz oil is an irregular, low-lying ria[3] coastline, which is composed mainly of small drowned river valleys and protruding rocky headlands. The Brittany coast is one of the most widely recognized ria coasts in the world, as a result of the writings of de Martonne (1903; 1906) and Guilcher (1948; 1958). Guilcher's (1958) text on coastal morphology is liberally endowed with references to and illustrations of the Brittany coast. A more recent publication by Chassé (1972) describes the morphology and sediments of selected segments of the spill site in great detail.

[3] "Rias may be defined as river systems partly or wholly flooded by the sea. The degree of drowning depends on the magnitude of the movement of base-level and on the altitude of the source of the rivers. The subaerial origin of rias is demonstrated by the occasional existence of incised meander as on the Aulne at Landevennec in the Rade de Brest." (Guilcher, 1958, p. 153)

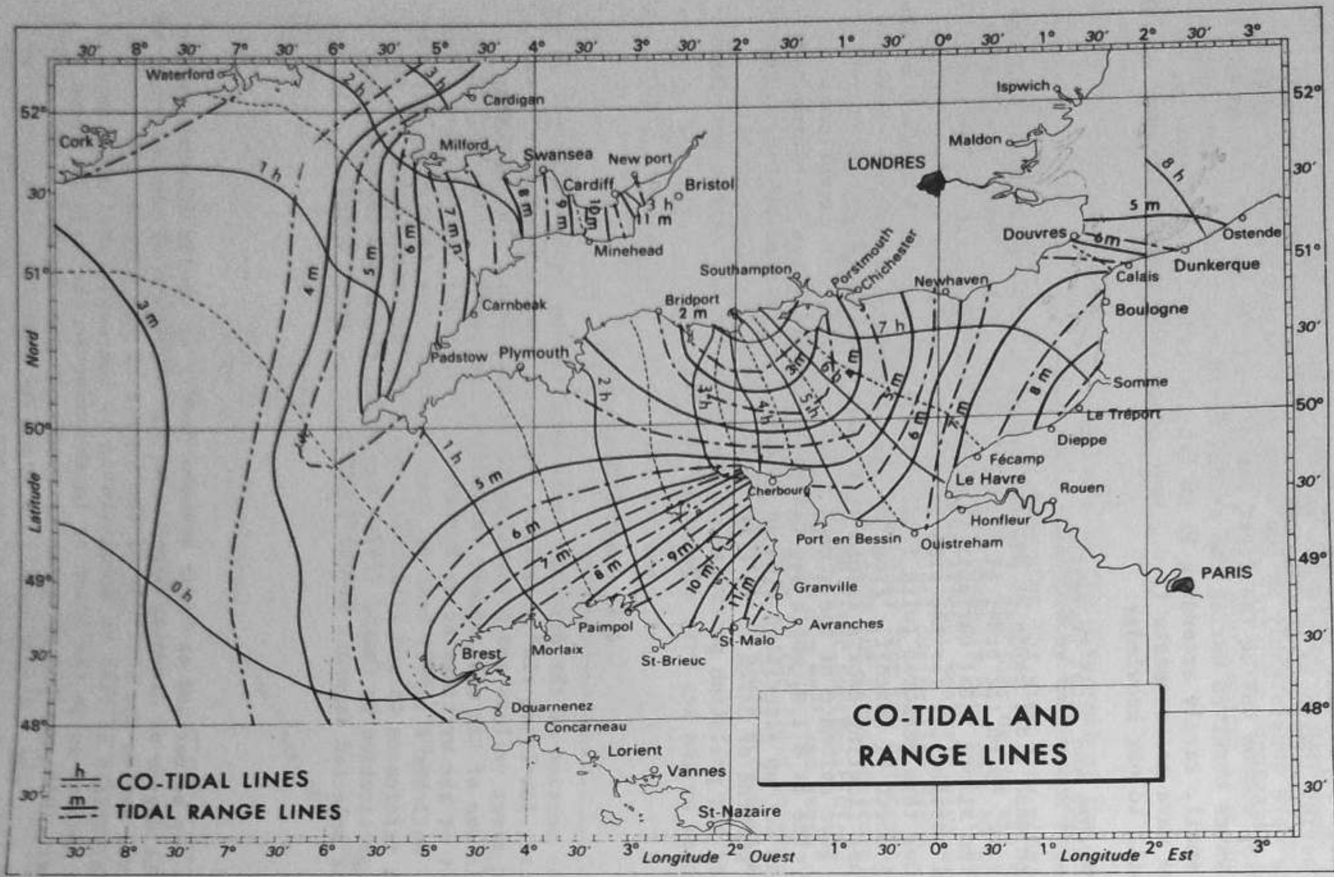


Figure 4.5. Tidal range lines for the English Channel (from French Hydrographic Service Pub. 551). Tidal range increases, going from 6 m at Brest to over 9 m at Paimpol.

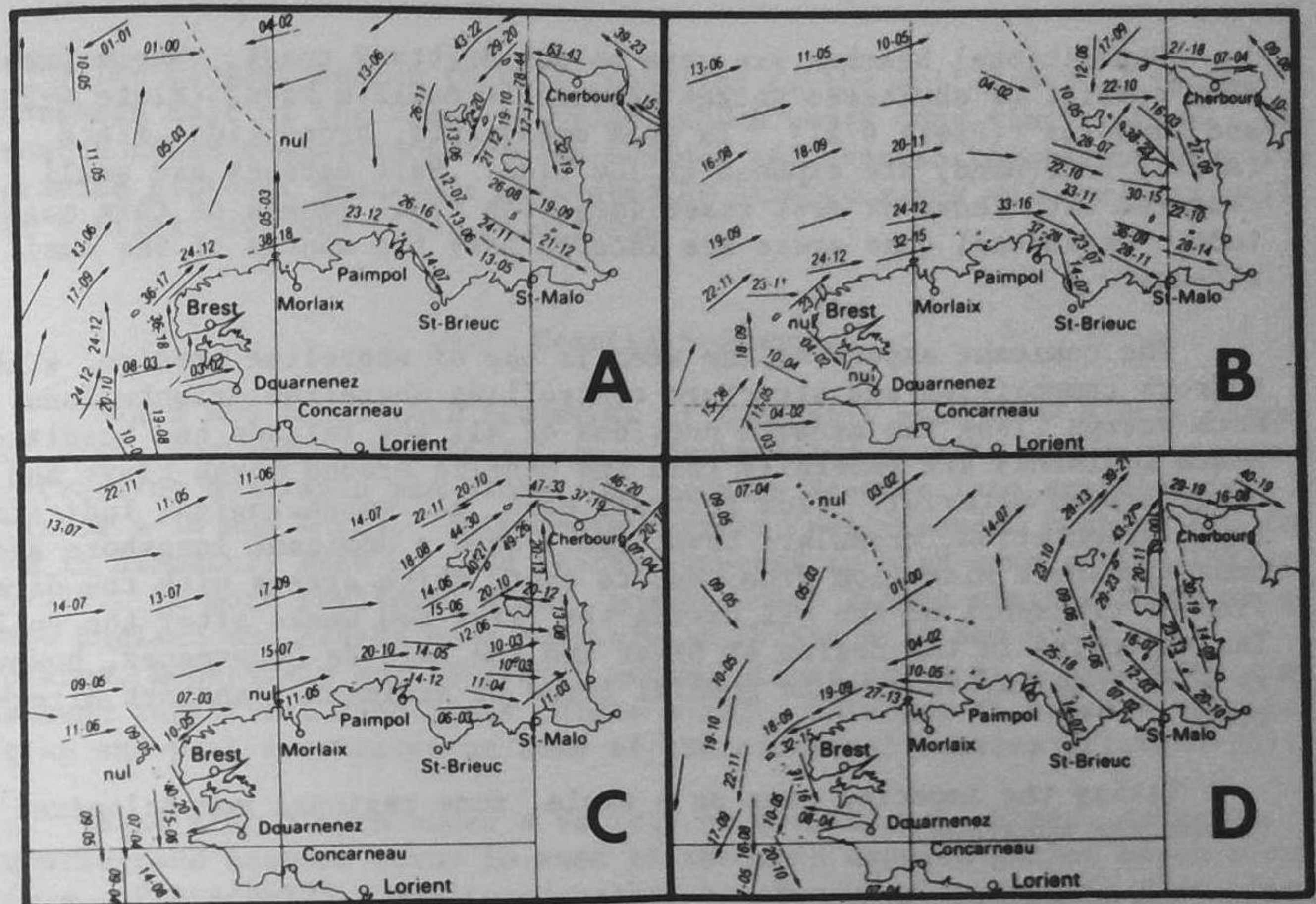


Figure 4-6. Currents (m/sec) for the English Channel north of Brittany (from French Hydrographic Service Pub. 551). (A) 6 hours before high tide at Cherbourg; (B) 4 hours before; (C) 2 hours before; and (D) during high tide at Cherbourg.

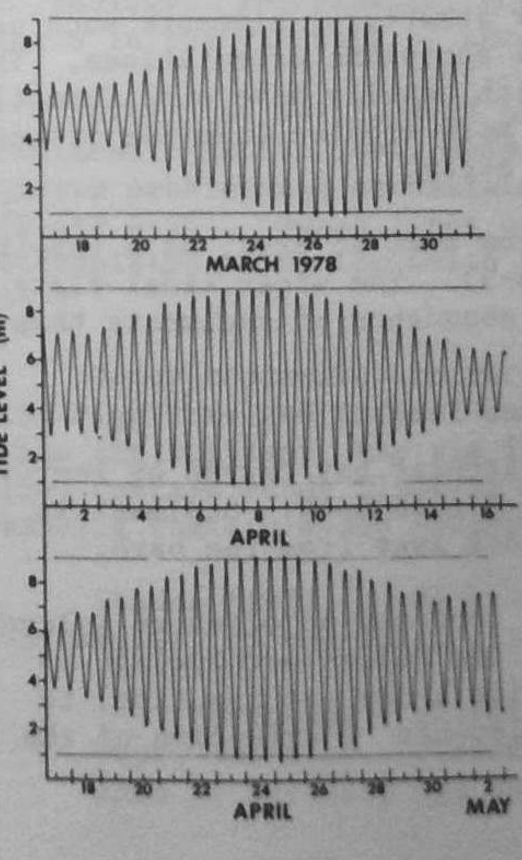


Figure 4-7. Tide curve for Morlaix from March 17 to May 2 (from French Hydrographic Service Pub. 785). Spring tides during March 25 to 28, coupled with an intense low-pressure storm, spread oil very high along the shoreline.

Depositional beaches are rare on the Brittany coast. Where present, they consist of sheltered pocket beaches, crenulate bays[4] (Plate 4-20), and tombolos[5] (Plate 4-21). In some embayments, broad tidal flats (mostly fine-sand) are exposed at low tide. Salt marshes are small compared with those of most coastlines with tidal ranges of this magnitude. Occasional dune areas are located near the mouths of the small streams.

The dominant aspect of the area is one of shoreline erosion, with bedrock composition and structure controlling shoreline orientations. Rock scarps flank the seaward portions of all the islands and headlands. Beach sediments are generally thin and overlie eroded marsh clays and other eroded material. From Portsall east, all morphological indicators (spit orientation, crenulate bays, etc.) show a dominant longshore sediment transport direction from west to east, which agrees with the direction of transport of the oil during the first two weeks after the spill. The shoreline in the region of Brest and the Baie de Douarnenez, however, is more complex, showing no general trend of sediment transport direction.

Taking the impacted area as a whole, some regional morphological trends are apparent:

(1) The shoreline in the large embayments of the Rade de Brest and Baie de Douarnenez are flanked by high cliffs with narrow intertidal zones. Coastline orientations are controlled by major structural elements, such as regional faults (e.g., the south shoreline of Baie de Douarnenez).

(2) Granite plutons which form massive headlands predominate along the northwest and northern shores. Minor structural elements such as minor faults and joints control local shoreline orientations. The western sides of those headlands, which usually have wide intertidal wave-cut platforms, have suffered more erosion than the eastern sides, which have steeper intertidal areas.

(3) Intertidal areas increase in width from west to east, as a result of the increasing tidal range (Fig. 4-5). The wider tidal flats to the east appear to contain a greater abundance of sediments than those to the west.

---

[4] A crenulate bay is an asymmetrical semicircular bay carved by refracting waves that has a shape resembling a fish hook. Sediment is normally transported up the shank of the hook away from the barb.

[5] A tombolo is a sand or gravel spit which connects an offshore island to the mainland or to another island. "In the Molène archipelago in Finistère, certain islets are connected twice a day (at low tide) to the larger islands and are called Breton 'ledenez' ('extension of the island')" (Guilcher, 1958, p. 90).

The closest analog to this coastline in the United States is the northern half of the coast of Maine, which bears many similarities. The most notable comparisons are the bedrock and coastal topography (massive granite plutonic headlands separated by drowned river valleys), as well as similar wave and tidal conditions.

4.7 Coastal Sediments

Beach and intertidal sediments of the spill site show a wide range of size, sorting, and composition. House-sized granite boulders occur at retreating headlands and along some arcuate beaches (see examples in Plates 4-16 and 4-22). Intermediate-sized, well-rounded cobbles (20 to 40 cm in diameter) make up some beaches exposed to high wave action (Plate 4-27). In more sheltered areas, gravel beach ridges similar to those of New England and Alaska have accumulated (Plate 4-14 and 4-15). In places, moderately sorted gravel accumulations occur as a high tide rim around intertidal sand flats (Plate 4-13). Thin gravel veneers overlie clay and peat substrates on some of the erosional beaches (Plate 4-33).

Sand also occurs under a variety of conditions. Steep, cuspate coarse-sand beaches occur in some of the more exposed pocket beach areas (e.g., Plate 4-12). Sheltered pocket beaches usually contain flat, fine-grained sand beaches (Plate 4-26). The finest sands are found in the coastal dunes that occur at several localities between Portsall and Roscoff (Plate 4-23).

A wide variety of sediment types may occur within a small geographic area because of the complexity of the nearshore and coastal morphology. For example, note the variation in grain size of the sediments in the vicinity of the tombolo illustrated in Plate 4-21.

After the spill, dead organisms became a part of the transported sediment. At St. Cava, dead cockles were transported along with quartz pebbles and accumulated in rows at the toe of the beachface (Plate 4-25). Swash lines of dead razor clams and heart urchins were accumulated along the beach at St. Michel-en-Grève on April 2 (Plate 4-7).

Muddy sediments are rare in the spill site, presumably because of the high wave and current energy conditions that prevail. Some of the rias (in Brittany, the ria is often called an aber, Guilcher, 1958, p. 154) contain muddy flats in their upper reaches, and the salt marshes usually contain muddy sediments.

Chassé (1972, p. 3) made the following comment about the sediment variability of the spill site (translated by Jacqueline Michel):

> "Brittany's shoreline offers a great diversity of headlands, bays, and rias. Present-day sediments are a complex mixture of sand of Tertiary age and aeolian silts, fluvia pebbles, and more

or less relict sand of Quaternary age (both Tyrrhenian and Flandrien). But all along this submerging coast of rias and incised marine gulfs (Morbihan, Bay of Douarnenez, Rade de Brest, Aber Wrac'h, Bay of Morlaix, etc.), only one sediment type is poorly represented, the aeolian quartz dune sands between 200 and 400 microns, which corresponds to the most mobile grain size."

Chassé presented detailed maps of the sediment distribution in several of the areas where oil accumulation was heaviest. These maps will provide a useful base for follow-up studies.

4.8 Methods of Study

The study of a major oil spill requires techniques, amenable to rapid implementation, that provide for maximum information gained with the least amount of field time expended. Large geographic areas have to be classified and sampled rapidly. In order to achieve this goal, we applied a modified version of the zonal method to the Amoco Cadiz oil spill site.

4.8.1 The Zonal Method

The zonal method was developed by Hayes and associates (first described by Hayes et al., 1973) in order to determine the geomorphic variation of large sections of coast. It has been applied in several areas of the world, including the southeast coast of Alaska (Hayes et al., 1976b) and during studies of the Metula, Urquiola, and Jakob Maersk oil spills (Gundlach and Hayes, 1978). A modified form of the zonal method has been used to determine the vulnerability of coastal environments to oil spills in several parts of Alaska under the sponsorship of NOAA's OCSEAP program. In a study of Lower Cook Inlet (for the State of Alaska), a total of 1216 km of coast was classified within 21 days by a team of three persons (Hayes et al., 1976a). A similar approach was taken during our study of the Amoco Cadiz oil spill.

4.8.2 Flights

Extensive aerial photography and tape descriptions were carried out during the following flights over the Amoco Cadiz spill site:

(1) March 21--Wreck site to Roscoff.
(2) March 30--Mont St. Michel to Roscoff.
(3) April 3--Portsall to St. Michel-en-Grève.
(4) April 20--Pointe du Raz to Portsall.
(5) April 28--Pointe du Raz to Roscoff.

These flights were taken for purposes of visual inspection of oil distribution along the shoreline, observation of oil transport and dispersal processes, and for interpreting shoreline morphology and sedimentation patterns.

4.8.3 Beach Stations

A total of 166 beach stations was visited (locations in Fig. 4-1). Stations of two types were established, F-stations (plain numbers) and AMC-stations (numbers preceded by AMC). A brief description of each station is presented under each section heading. At the 147 F-stations, the site was visually inspected, photographs were taken, and observations were recorded on tape. Work at the 19 AMC-stations included the following:

(a) A topographic profile of the beach (at low tide) was measured. The profile is measured by the horizon-leveling technique of Emery (1961). As the profile is measured, notations are made concerning all relevant changes of the beach, including the nature and occurrence of the oil. Permanent stakes were established to mark the location of the profile. Six of the profiles were resurveyed twice during the first visit and one was resurveyed three times. All of these stations will be revisited to repeat the surveys.

(b) Three equally spaced sediment samples were collected. These were taken for the purpose of characterizing the beach with respect to its oil penetration and burial. These samples have been analyzed for textural characteristics (mean grain size, sorting, etc.) in the laboratory and they are discussed below; 53 sediment samples were collected on the first trip.

(c) Trenches were dug to determine the distribution of buried oil. Each trench was sketched and photographed in detail.

(d) A sketch was drawn to show the general coastal geomorphology and the surficial oil distribution. Several examples are given in discussions of the different shoreline sections.

(e) A number of photographs were taken of all aspects of the beach.

4.8.4 Oil Distribution

Distribution Maps

The occurrence of oil along the shoreline was mapped both from the air and from the ground during both visits to the site. The oil distribution for the two time intervals is shown on Figures 1A and 1B.

Calculation of Tonnage

During study of each AMC-station, the thickness of mousse was measured at a maximum interval of 5 m along the profile line. The percent oil coverage of the surface was also noted. The assumed volume of mousse present is the measured thickness multiplied by the overall length of the beach as measured on 1:25,000 scale topographic maps. Where oil did not cover the entire area, appropriate reductions were made. Buried oil was noted and photographed. An estimate of the amount buried was made by calculating the volume of oiled sediment and assuming that 10% of this volume was mousse. The 10% value was derived from analyses by Anne Blount (of our group) on over 50 oiled sediment samples from the Metula site. All mousse was assumed to be 60% water. The specific gravity of the oil, used to calculate total metric tonnage, was assumed to be 0.85 gm/cc.

In order to derive the total amount of oil on the beaches in the spill area, an average oil content per km of shoreline was calculated from our 19 AMC-stations. The amount of similarly oiled coastline was then measured on 1:25,000 scale topographic maps and multiplied by this value. This was done for both study periods (March 19 to April 2 and April 20 to 28) to determine the net change.

4.8.5 Observations of Biological Impact

Because of the emergency situation surrounding the spill as well as the opportunity to contribute to a basic understanding of oil spill impacts, a special effort was made by our group to observe the biological effects of the spill, although this was not our primary objective. Notes were taken on tape, and numerous photographs were taken wherever biological damage was observed. Some of our general observations are presented in our descriptions of the individual coastal sections for the record. For a complete discussion of the investigations of biological processes, refer to Chapter 5.

4.8.6 Chemical Samples

Samples of mousse and oiled ground water were collected at selected localities for chemical analyses (during both trips). These samples were passed on to the SOR team or to John L. Laseter of the University of New Orleans' Center for Bio-Organic studies for processing.

4.8.7 Observations of Cleanup Activities

Wherever cleanup was observed in progress, photographs were taken (see Plates 4-4, 4-5, 4-8, 4-9, 4-11, and 4-19) and conclusions were recorded on tape in order to note in detail the success or failure of each method. Cleanup was studied in depth by Roy Hann and his associates from Texas A & M University (see Chapter 6). Reference is made to the cleanup effort in this chapter where either (a) the cleanup technique affected the normal beach processes, or (b) an understanding of beach processes would aid in the cleanup exercise.

4.9 Field Observations of Oil Impact

For purposes of description, the impacted coastline is divided into 11 separate sections (located on Figures 4-8 and 4-9). The individual sections will be discussed in sequence from west to east. Observations made during both of the field visits are included.

4.9.1 Section I--Pte. du Raz to Penfoul

Section I is located to the south-southeast of the Amoco Cadiz wreck site (Fig. 4-10). The coastline generally consists of high-energy rocky headlands with small pocket beaches. Cliffs over 40 m in height are common toward the south. Although the tidal range is 5.5-6.0 m, little more of the coast is actually exposed during low tide than at high tide because of the steeply-dropping offshore bathymetry. This is in distinct contrast to the many wide tidal flat systems that lie to the north and northeast.

Oil impact, March 17-April 2

During the first two weeks after the grounding, little or no oil was transported to this area. Winds were blowing strongly from the west and southwest. A survey of station F-82 and stations further north on March 31 revealed only a few small tar blotches (of unknown origin) on the rocks. A sample was taken for chemical analysis.

Oil impact, April 20-28

A distinct change in oil distribution was observed during our second study period. During the aerial survey on April 20, heavy oil accumulations were observed as far south as Pointe du Raz, 126 km (77 miles) from the wreck site. Very heavy oil accumulations were observed at station F-104 (Fig. 4-10) and northward. A photograph of station F-82 that was taken on the following day is presented in Figure 4-11. Stations F-97 to F-103 were lightly to moderately oiled. Table 4-1 summarizes oil impact for this area. A photograph of a newly oiled area near Argenton (F-109) is presented in Figure 4-12. As observed during the aerial survey on April 20, moderate to heavy oil accumulations were found at (a) beaches near Camaret, (b) in small pocket coves along the cliffs from Douarnenez to Pointe du Raz, and (c) at the beach at Pointe du Raz. Lighter accumulations were observed at Ile de Sein, located offshore of Pointe du Raz. The last two areas mark the most southerly extension of major contamination from the Amoco Cadiz.

The heavy oiling of this section during April was a result of the offshore winds of March 28-31 followed by strong south/southwest winds during April 2-10. The wind at this time blew ashore much of the oil that was still at sea, therby causing the oiling of an additional 91 m of shoreline.

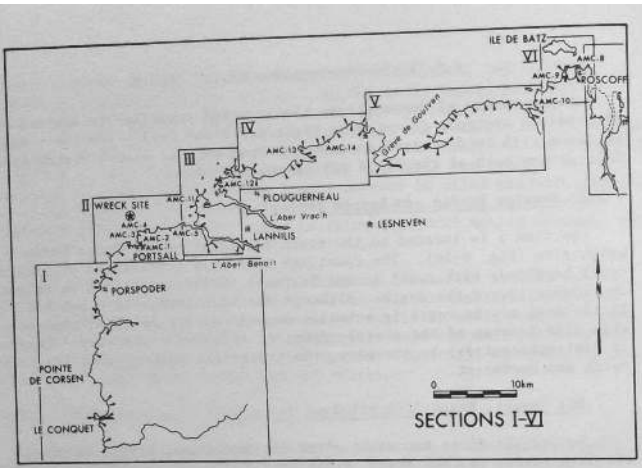


Figure 4-8. Locations of Sections I to VI of the spill study area.

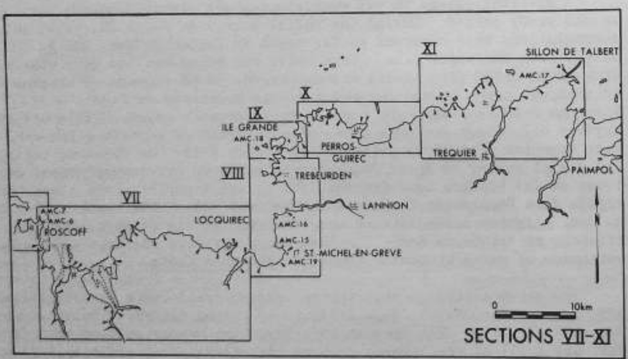


Figure 4-9. Locations of Sections VII to XI of the spill study area.

Figure 4-10. Locations of observation stations in Section I, Pointe du Raz to Penfoul. No oil was in this area during the first two weeks of the spill. The pattern between heavy lines indicates oil distribution as observed during second study period (April 20 to 28). Pluses indicate moderate to heavy oiling of upper intertidal rocks and/or beachface; circles indicate moderate oiling of lowtide terrace; dot pattern indicates light oiling on rocks or beachface. Mousse swashes and heavy oiling were observed south of F-97 during aerial survey of April 20. By second flight on April 28 the oil was no longer present.

Figure 4-11. Heavily oiled rocks at station F-82 on April 21. Three weeks before, the area was observed in detail and found to be clean except for some small tar blotches. Re-oiling occurred as a result of a wind shift during the early part of April.

Figure 4-12. Heavily oiled pocket cover near Argenton (F-109) on April 28. Mousse also covers the surface of the water.

Table 4-1. Field observations of oil distribution at stations of Section I, Pointe de St. Mathieu to Penfoul.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-97	21 Apr	Pointe de St. Mathieu A rocky platform with a small cobble beach.	A few oil blotches along the swash line - mostly small; a few 5 cm tar or mousse balls; rocks spotted with small amount of mousse. Area seemed biologically productive - much algae and limpets.
F-98	21 Apr	Grève de Porsliogan A small cove/pocket, medium grained sandy beach surrounded by a rocky area.	Light oil at all swash lines. Algae productive. Many worm burrows. Some oil burial of 5 cm - very minor.
F-99	21 Apr	Le Conquet - Beach A small sandy pocket beach surrounded by a rocky area.	Very light oil swash lines with more oil along the upper swash line and on some of the rocky areas.
F-100	21 Apr	Pointe de Kermorvan A boulder beach.	Small amounts of mousse in water. Heavy oiling of boulder beach on the north side of the lighthouse.
F-101	21 Apr	Le Conquet-Harbor (East side) Large sand flat exposed at low tide.	Free of oil - boom at harbor entrance.
F-102	21 Apr	Plage de Blancs-Sablons Wide sandy (fine to medium-grained) beach. Rocks at both ends of beach.	Oil streaks over the entire intertidal portion of the beach. Heavy mousse on rocks in NE corner. Oil pools of mousse located on beach - some mousse in water.
F-103	21 Apr	Port Illian Small pocket beach protected by a jutting rocky headland. Fine-sand on beachface; some gravel on the lower portions.	Oil streaked swash lines. Small mousse patches left on the beach surface.
F-104	21 Apr	Rubian Coarse-sand beach with many cobbles especially on lower beach.	Heavily oiled rocks; moderately oiled coarse-sand beach. Oil pools 5 cm thick in some areas and a coating on the boulders at the base of the sand. Oil buried due to clean-up activity.
F-105	21 Apr	l'Aber Ildut - Estuary Narrow entrance with 2 booms present.	Oiled seaweed along the edge of the channel. Oil sheen on both sides of the booms.
F-106	21 Apr	Melon - South side Small rocky beach with little wave activity.	Entire intertidal zone heavily oiled. Very heavily oiled rocks and mousse in water.
F-107	21 Apr	Melon - North (harbor) A u-shaped harbor with an island offshore to protect it. Fine-sand beach.	Very heavily oiled beach. Rocks in northern pocket very heavily oiled. Active clean-up effort.
F-108	21 Apr	Porspoder Fine-grained pocket beach with rocky headlands on both sides.	Rocks heavily oiled; 10-15 cm thick oil on the beach. Mousse in water. Clean-up operation in effect.
F-109	21 Apr	Argenton Small cove, very well protected fine-grained beach.	Thin oil layer covers most of the beach. Heavy oil along edge of the pocket cove. Small amount of mousse in water.
F-110	21 Apr	Penfoul Small fine-grained estuary.	Heavy oiling on both sides of the estuary; slicks seen over entire area. Clean-up operation in effect.
F-82	31 Mar- 21 Apr-	Pointe de Landunvez High energy boulder beach on wave-cut granite platform.	-minor tar blotches (3-5 cm) on rocks. -heavily oiled rocks and boulders with some mousse in the water.

Table 4-2. Field observations of oil distribution at stations of Section II, St. Sampson to Les Dunes-East.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-81	31 Mar	St. Sampson Boulder beach on wave-cut rock platform; high energy (1 m waves present).	No oil.
F-1	19 Mar-	Trémazan Boulder beach on wave-cut rock platform (close to wreck site).	-light mousse in water and along shore.
	20 Mar-		-very heavy oiling, oncoming waves 2 m in height.
	31 Mar-		-only very small scattered blotches of oil remain.
	21 Apr-		-heavily reoiled.
AMC-1 (F-2)	20 Mar (F)- 22 Mar-	Portsall Sheltered embayment, with seawalls, small coarse-grained beaches and fine-sand tidal flat.	-very heavily oiled beach and tidal flat; extensive skimming operation.
	31 Mar-		-still heavily oiled beach; minor oiling on tidal flat.
	21 Apr-		-still heavily oiled beach; some stationary oil on tidal flat; heavy oiling of rocks and seaweed along eastern shore; little oil on surface of water; extensive shoreline clean-up activity.
AMC-2	22 Mar 31 Mar 21 Apr	Portsall Angular, gravel beach; fine-sand tidal flat.	Heavily oiled beach; clean tidal flat.
AMC-3 (F-3)	20 Mar (F)- 22 Mar- 31 Mar-	Portsall-North Cobbles against a seawall along the upper beachface; coarse-sand on rest of beachface; fine-sand low-tide terrace with some algae covered rocks.	-heavily oiled beach, upper low-tide terrace and rocks.
	21 Apr-		-moderate coverage of beachface with thick (10 cm) mousse swashes; still heavily oiled rocks.
F-84	31 Mar-	Prat Leac'h-Kerras 0.5 km sand pocket beach with eroding sedimentary backshore.	-very heavily oiled beachface; extensive clean-up operation.
	21 Apr-		-clean beach but new erosion scarp formed along the backshore.
AMC-4 (F-4)	23 Mar-	Les Dunes-West Three pocket, sand beaches within a large sheltered cove. A fine-sand tidal flat is exposed at low tide; each beach has a clay base with eroding clay scarp along the backshore.	-very heavily oiled beachface and upper tidal flat along eastern shore. Very large amphipod kill. Center beach has moderate oiling; western beach clean.
	31 Mar-		-heavily oiled upper beachface.
	21 Apr-		-heavy oil swashes; front-end loaders removing oil and sand from beachface.
AMC-5 (F-5)	20 Mar (F)-	Les Dunes-East Large deposition area with a grass stabilized dune field. A flat profile fine-sand beach/low-tide terrace abuts an eroding dune scarp.	-moderate oil streaks on eastern side; fewer on western side.
	23 Mar-		-very heavy oil covering the entire beach on east side and on upper beach of west side.
	26 Mar-		-very heavy oil on east side of stream; large amount of oil buried on west side.
	31 Mar-		-clean east side; very heavy oil on west side.
	22 Apr-		-very light oil swashes; some oil burial on both sides of stream.

During our last aerial survey on April 28, no oil was observed at Camaret and Pointe du Raz. Nor was oil seen on the surface of the water. However, north of station F-97, the oil appeared the same as before. A large cleanup operation also remained active in the area.

Although we did not observe any oil on the beaches south of Pointe de St. Mathieu (F-97) from the air, it should be noted that in all likelihood a ground survey would find light swashes of small mousse balls on these beaches. These features were very common throughout the study area, and were even found on the beach next to the CNEXO lab at Brest.

Summary

Section I proved to be a surprise to us:

(1) It had become very heavily oiled more than three weeks after the spill, illustrating the ability of massive quantities of oil still to be transported several weeks after initial spillage.

(2) Thick mousse concentrations were observed on the water's surface along the cliffs between Douarnenez and Pointe du Raz, a full month after the beginning of the spill.

(3) Heavy oil accumulations extended southward to Pointe du Raz, a total of 126 km (77 miles) from the wreck site.

4.9.2 Section II--St. Sampson to Les Dunes-East

This section, shown on the maps of Figures 4-13 and 4-14, is located in the vicinity of the wreck site; it was the first area to be oiled (Table 4-2). South of station F-1 (Fig. 4-13), the shoreline consists of an eroding wave-cut platform in granite that has a shoreward scarp 3 to 15 m in height. The intertidal platform is covered with large boulders.

Portsall Harbor

Week of March 20. Stations AMC-1 and AMC-2 (Fig. 4-13) are both located in Portsall Harbor, a sheltered, relatively low-energy environment. Figure 4-15 is a detailed map of the Portsall area which shows the oil distribution at first impact and at one month later. During the first week after the wreck, a large oil mass was located in the harbor. The profile at station AMC-1, which crosses the embayment (Fig. 4-15), was measured at that time (see field sketch in Fig. 4-16). As the profile was surveyed, measurements of oil thickness and estimates of percentage of oil cover were made as often as warranted. A plot of these measurements along the surveyed topographic profile is presented in Figure 4-17. Sediment grain size data for the A, B, and C samples are presented in Table 4-3. All the sediments are poorly sorted, with

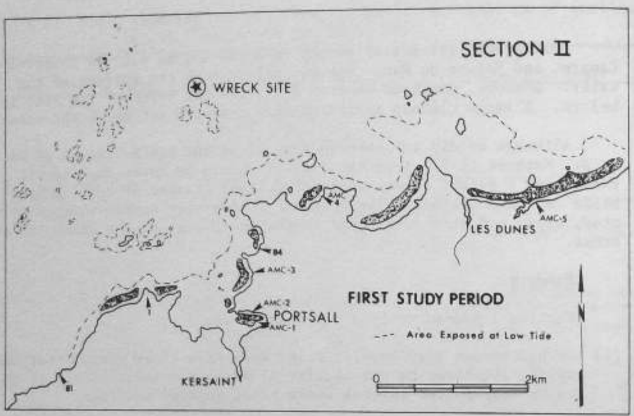


Figure 4-13. Locations of observation stations in Section II, the Portsall area, during the first study period (March 19 to April 2). Heavy oil accumulations are indicated by the dark-stippled pattern.

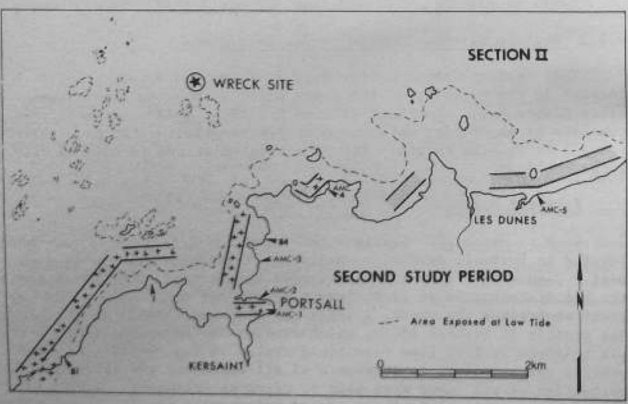


Figure 4-14. Oil distribution for Section II for second study session, April 20 to 28. Heavy and light oil coverage are indicated by the plus and light-dot patterns, respectively.

Table 4-3. Grain size data for AMC stations of Section II. All statistics are calculated according to Folk (1968).

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-1A	0.691	CS	0.101	1.594 (PS)
AMC-1B	0.952	CS	0.197	1.413 (PS)
AMC-1C	1.954	MS	-0.134	1.350 (PS)
AMC-2A	-4.0	P		(PS)
AMC-2B	1.492	MS	-0.093	1.119 (PS)
AMC-2C		no sample		
AMC-3A	-7.0	C		(PS)
AMC-3B	2.415	FS	-0.571	1.243 (PS)
AMC-3C	0.123	CS	-0.042	1.316 (PS)
AMC-4A	0.503	CS	-0.263	1.024 (PS)
AMC-4B	0.847	CS	-0.003	0.561 (MWS)
AMC-4C	2.082	FS	-0.383	0.978 (MS)
AMC-5A	1.047	MS	-0.001	0.759 (MS)
AMC-5B	2.415	FS	-0.207	0.593 (MWS)
AMC-5C	2.026	FS	-0.134	0.757 (MS)

[1]Size Class

C = cobbles
P = pebbles
CS = coarse sand
MS = medium sand
FS = fine sand

[2]Sorting

MWS = moderately well sorted
MS = moderately sorted
PS = poorly sorted

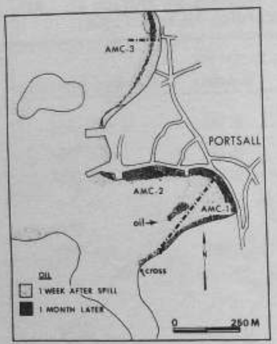


Figure 4-15. Detailed location map for the Portsall area. Oil distribution, as observed during our two study sessions, is indicated.

the coarsest sediment occurring near shore. Our calculations indicate that 50.2 metric tons of oil were present in the AMC-1 area during the first survey (after subtracting 60% for water content of the mousse)[6]. This relatively low value is attributed to the lack of very thick accumulations on the tidal flat surface.

Clean-up activities initially consisted of the deployment of several tank trucks with skimmers. Their ability to remove the floating oil was restricted to periods of high tide, since the harbor is dry at low tide (see Plate 4-9, 4-19, and 6-4).

During the survey of AMC-1, we counted several dozen polychaetes on the surface of the flat in a generally moribund condition. However, several live polychaetes and small shrimp were found in the sediment, even though the interstital water was seriously contaminated with oil. By walking around on the flat, we found five different species of dead fish (Plate 5-20). Each had oil-blackened gill structures.

[6] Inasmuch as the oil was usually distributed in distinct masses, these oil volume calculations are an attempt to include the whole mass in a given area. This particular calculation includes all the oil in the eastern and southeastern portion of Portsall Harbor (Fig. 4-15), as determined from ground surveys and aerial photography.

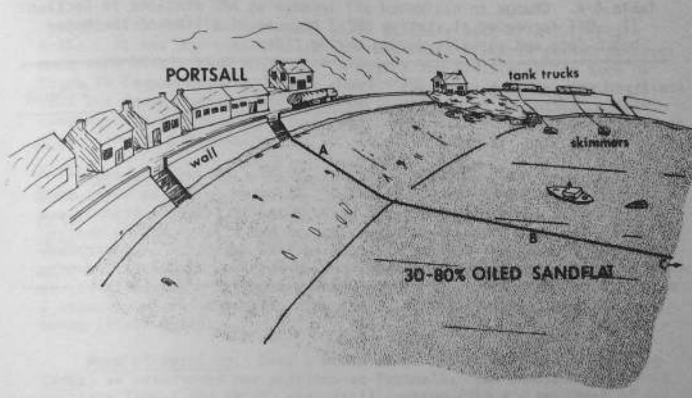


Figure 4-16. Sketch of station AMC-1 (Portsall) on March 22. Sediment sampling sites A, B, and C are indicated.

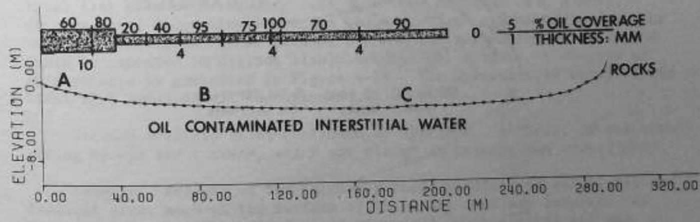


Figure 4-17. Topographic beach profile and oil coverage for station AMC-1 on March 22. The thickness of the shaded line is roughly proportional to the oil thickness. Letters A, B, and C indicate sediment sampling sites.

Table 4-4. Change in estimated oil tonnage at AMC stations in Section II. Oil increased at station AMC-2 because of oiling of the upper beach face and seawalls during spring tides.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-1	22 Mar	50.2	22 Apr	7.3	-85.46
AMC-2	22 Mar	1.8	22 Apr	2.4	+33.00
AMC-3	22 Mar	44.6	22 Apr	5.5	-87.70
AMC-4	23 Mar	284.1	31 Mar	36.9	-87.01
			22 Apr	2.5	-93.22
AMC-5	23 Mar	1146.9	22 Apr	2.5	-99.80

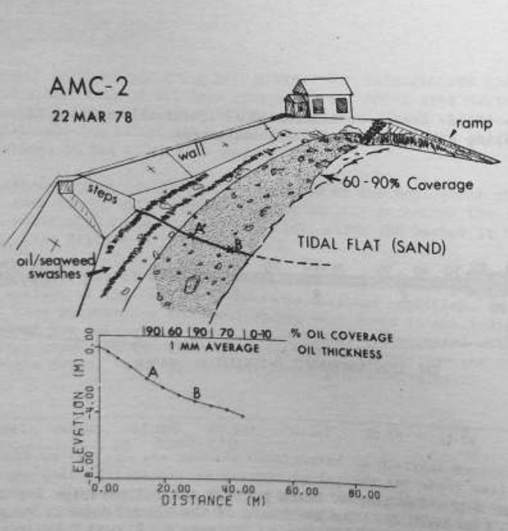


Figure 4-18. Sketch and topographic beach profile for station AMC-2 on March 22. A thin coating of oil was present on the beach at this time. After the spring tide conditions of March 25-28, the coating of oil extended 1.5 m up the seawall.

Station AMC-2 is located a short distance west of AMC-1 (Fig. 4-15). It was surveyed because it represented a coarse gravel environment with little wave activity. A sketch and profile of the area on March 22 is presented in Figure 4-18. Grain size data for the beachface area are presented in Table 4-3. During the March 22 survey, a thin coating of oil covered the lower beachface. The total volume present at that time was 1.8 tons.

Week of March 29. The beachface at AMC-1 was 100% covered by a thin layer of oil on March 29. Oil coverage of the intertidal flat area was reduced to 10%-15%. At station AMC-2, the beachface and lower portion of the seawall had become completely covered with oil. From observations, it became obvious that the majority of the oil was lifted off the tidal flat and transported shoreward to the beaches and seawalls as the tide rose. By March 29, the clean-up operation had changed from a skimming operation to cleaning the oiled walls with high-pressure hoses (Plate 6-14).

Week of April 20. Over a month after the grounding of the Amoco Cadiz, we resurveyed our stations at Portsall. The beachfaces of both stations (AMC-1 and AMC-2) were still covered with a 2 mm layer of oil. At AMC-2, an apparently new layer of mousse, brown in appearance, had been deposited at the last high tide swash line. The surface of the tidal flat had a few light oil sheens and a few large patches (approximately 30 m in diameter) of sediment-bound oil. The algal-covered rocks on the western side of the harbor were 80%-90% covered by brown mousse. Our calculations showed 7.3 metric tons present at AMC-1 (85% decrease) and 2.4 metric tons at AMC-2 (33% increase; see Table 4-4).

It appears that while most of the incoming oil was lifted off the tidal flat with each incoming tide (observed on March 22), a small percentage of it eventually became sediment-bound and stabilized on the bottom of the flat. These patches are not subject to resuspension and would be expected to degrade slowly by physical action. A diagram of this process is presented in Figure 4-19. The interstitial water of the tidal flat remained oil-contaminated.

Cleanup activity still continued on April 22. At least 30 men were raking up oil and seaweed, which was placed in buckets and carted away.

Summary. Because of the initially large quantity of oil within the Portsall area, much of the surface of the tidal flat was covered. As time progressed and the tidal range increased, much of this oil was lifted and transported shoreward. However, some oil did become sediment-bound and remained on the bottom. By April 22, the nearshore areas, especially the rocks with algae on the west side of the harbor, were still covered with oil. In addition, some oiled sediment patches remained in the center of the tidal flat. All interstitial water was still oil-contaminated.

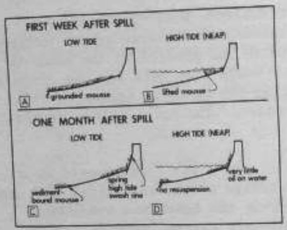


Figure 4-19. Observation of oil response at Portsall. During the first week after the spill, most of the oil lifted off the surface of the sand flat with every incoming tide. During our second survey mousse mixed with the sediment remained on the sand flat and beachface even as the tide flooded. Only a light oil sheen was visible on the surface of the water.

Station AMC-3

AMC-3 is located in a semi-sheltered area north of Portsall, somewhat closer to the wreck than stations AMC-1 and AMC-2 (Fig. 4-13). The station consists of a small beach composed of mixed sand and cobbles, which has a low-tide terrace with some algal-covered rocks. Grain size data are presented in Table 4-3. A sketch of the site during maximum coverage by oil (on March 31) is shown in Figure 4-20. There were approximately 44.6 metric tons of oil on this beach at that time. The leaching of ground water from the beach removed 10%-15% of the total surface cover. Also, in the area where the stream crossed the beach at low tide (Fig. 4-20), all oil was removed. This observation suggests that a similar technique (i.e., using flowing water to wash oil into collecting basins or troughs) could be used to clean similar beaches with a great deal of efficiency.

The major difference between our site surveys on March 22 and 31 at AMC-3 was the progressively higher oiling of the beach and seawall as a result of the spring tides of March 25 through 28. The amount of oil present did not significantly vary between the two visits. On March 31, there was an extensive cleanup operation taking place in which mousse and seaweed debris were raked, placed in buckets, and then dumped into a large metal container. A screen separated the newly added seaweed from a pool of oil below. Soldiers forced the oil through the screen by stomping.

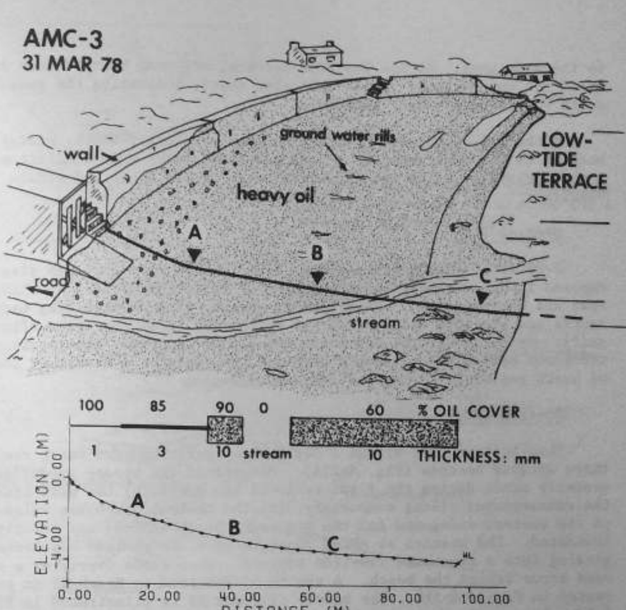


Figure 4-20. Topographic profile and oil coverage at station AMC-3 on March 31. High spring tides of March 25-28 were responsible for spreading oil up the wall behind the beach. Sediment sampling sites A, B, and C are indicated.

By April 21, most of the oil was gone from the area. An apparently new mousse swash line formed along the upper beachface. There were also some light oil streaks across the beach. The cobble area was still as heavily oiled as before. We calculated that 5.5 metric tons of oil were present on April 21, a reduction of 88% (Table 4-4).

In terms of biological damage, the most impressive observation was the presence of thousands of dead amphipods along the uppermost portion of the beach (by the steps). In contrast, new grass was found growing in the same area. On the low-tide terrace, new worm burrows were common. Oiled but empty cockle shells were also found, indicating the possible death by oiling of these organisms.

No burial of oil was observed on this particular beach, partly because of the occurrence of a hard peat-like layer from a relict marsh a short distance below the surface of most of the upper and middle beachface.

Station F-84

F-84 (Prat Leac'h-Kerros; Fig. 4-13) was an area that was also exposed to an extremely large quantity of oil. The entire intertidal zone was heavily oiled. An extensive cleanup program utilizing many trucks and tractors was carried out during the first few weeks after the spill. By April 21, the beach was 95% clean. However, some erosion of the scarp behind the beach had occurred, possibly as a result of removal of beach sediments during the cleanup operation.

Station AMC-4

This station lies within a northwesterly-facing cove which contains three arcuate beaches (Fig. 4-21A). Because of the strong prevailing westerly winds during the first weeks of the spill (a) the west side of the cove escaped oiling completely; (b) the central beach was oiled only on the eastern side; and (c) the remaining beach (AMC-4) was heavily inundated. The station at AMC-4 consists of a coarse-sand beachface grading into a fine-sand low-tide terrace. Dune sands overlying a clay base occur behind the beach. A sketch of the area on March 31 is presented in Figure 4-21B. The survey of March 23 is illustrated in Figure 4-22. Between March 23 and 31, the quantity of oil on the beach had decreased from 284 to 37 metric tons (see Table 4-4). During that same time interval, a total of 14.5 m^3 of sand was eroded from each meter of beach width (see Fig. 4-23). The cause of this extensive erosion was either the storm waves during the week of March 22 or the cleanup method applied, or possibly, a combination of the two. A small amount of recovery had already occurred when the profile was measured on March 31, in that some oil burial had taken place at the mid-beachface area and a small neap berm had formed.

The high spring tides of late March permitted the waves to wash oil high up onto the dune scarp (see sketch of March 31 in Fig. 4-21). Thousands of dead amphipods, identified by Jeff Hyland as Talitrus saltator (an upper intertidal species), littered the dune scarp (see Plate 4-24).

By April 21, deposition of 475 m^3 of sediment had occurred along the central portion of the beach (Fig. 4-23B). Oil was buried 20 to 25 cm by new sand. The beach appeared quite clean with only a light mousse swash along the last high tide swash line. Oil volume further

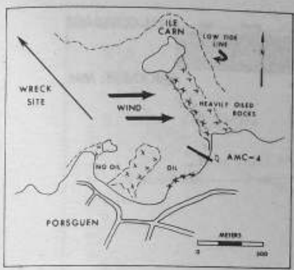


Figure 4-21A. Detailed location map and oil coverage for station AMC-4 during initial oiling.

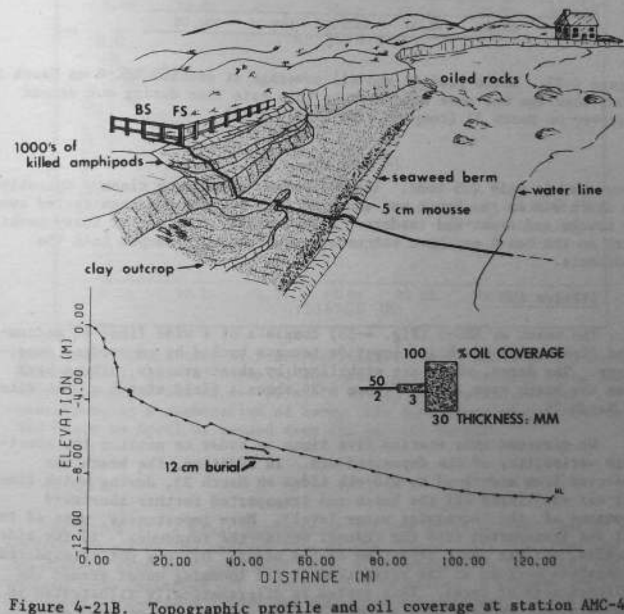


Figure 4-21B. Topographic profile and oil coverage at station AMC-4 on March 31. During the previous week, the shoreline had eroded significantly back, removing most of the oil from the lower beachface and exposing a relict red clay surface. Thousands of dead amphipods (Talitrus saltator) littered the dune scarp (Plate 4-27).

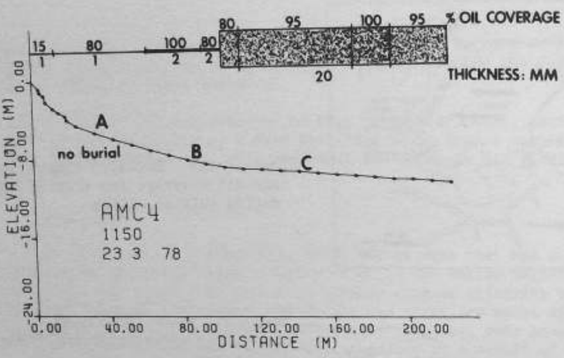


Figure 4-22. Beach profile and oil coverage at station AMC-4 on March 23. Oil coverage was more extensive on this date than during our second survey on March 31 (compare with Figure 4-21).

decreased to only 2.5 tons. There remained an ongoing cleanup operation in which oil on the beach was shoveled into buckets and then carted away by trucks and front-end loaders. Unfortunately, the use of heavy machinery on the beach may have succeeded in working oil deeper into the sediments.

Station AMC-5

The beach at AMC-5 (Fig. 4-13) consists of a wide fine- to medium-sand (Table 4-3) beach and low-tide terrace backed by an eroding dune scarp. The dunes, which are stabilized by short grasses, extend back from the beach over 1 km. Figure 4-24 shows a field sketch of the site on March 26.

We surveyed this station five times in order to monitor the short-term variability of the deposited oil. In addition, the beach was observed from mid-flood to mid-ebb tides on March 23, during which time all oil was lifted off the beach and transported further shoreward (because of the increasing water level). More importantly, most of the oil was transported into the channel behind the foredunes. As the tide receded, oil was again deposited on the beach. Oil was not transported alongshore because of the refraction of the incoming waves around the offshore mass of rocks. This system is diagramatically illustrated in Figure 4-25. We call this a tombolo effect. The role of the tombolo effect in causing localized oil deposition was observed in several other localities.

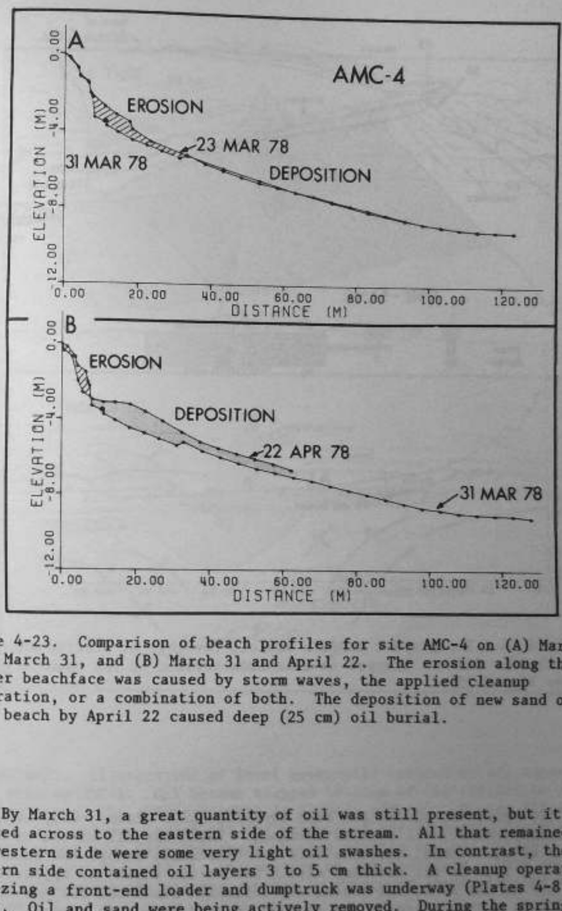


Figure 4-23. Comparison of beach profiles for site AMC-4 on (A) March 23 and March 31, and (B) March 31 and April 22. The erosion along the upper beachface was caused by storm waves, the applied cleanup operation, or a combination of both. The deposition of new sand on the beach by April 22 caused deep (25 cm) oil burial.

By March 31, a great quantity of oil was still present, but it had shifted across to the eastern side of the stream. All that remained on the western side were some very light oil swashes. In contrast, the eastern side contained oil layers 3 to 5 cm thick. A cleanup operation utilizing a front-end loader and dumptruck was underway (Plates 4-8 and 6-31). Oil and sand were being actively removed. During the spring tides of a few days earlier, the grassy areas along the stream channel behind the foredunes became heavily oiled. This area was being cleaned by bucket and shovel.

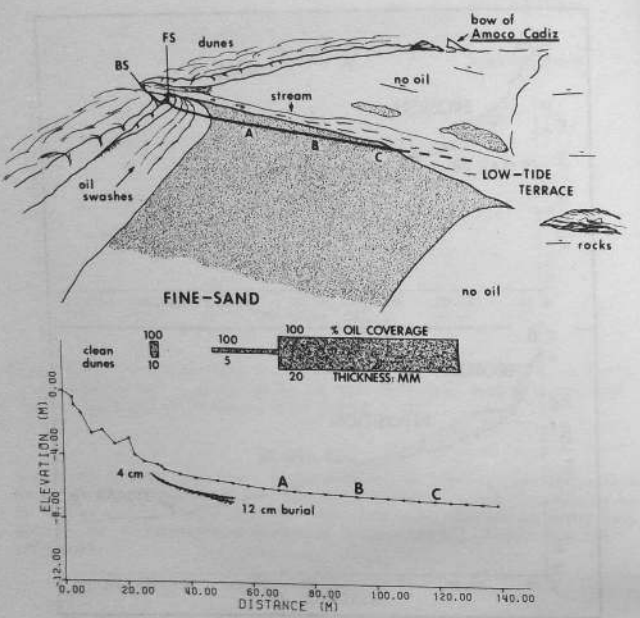


Figure 4-24. Topographic profile and oil coverage at station AMC-5 on March 26. Oil was trapped in this area because of the tombolo effect (see Fig. 4-25).

By April 22, the entire area appeared quite clean. Only light (probably recent) oil swashes remained. There was oil burial on both sides of the stream, but even this was relatively minor. We estimate that 2.5 tons of oil remained across the entire area. It appears that the use of the front-end loader was effective since the oil was thickly pooled in a single area. The removal of sand from this area will probably not prove to be a serious problem because the wide dune area behind the beach should provide adequate sand to replenish the beach.

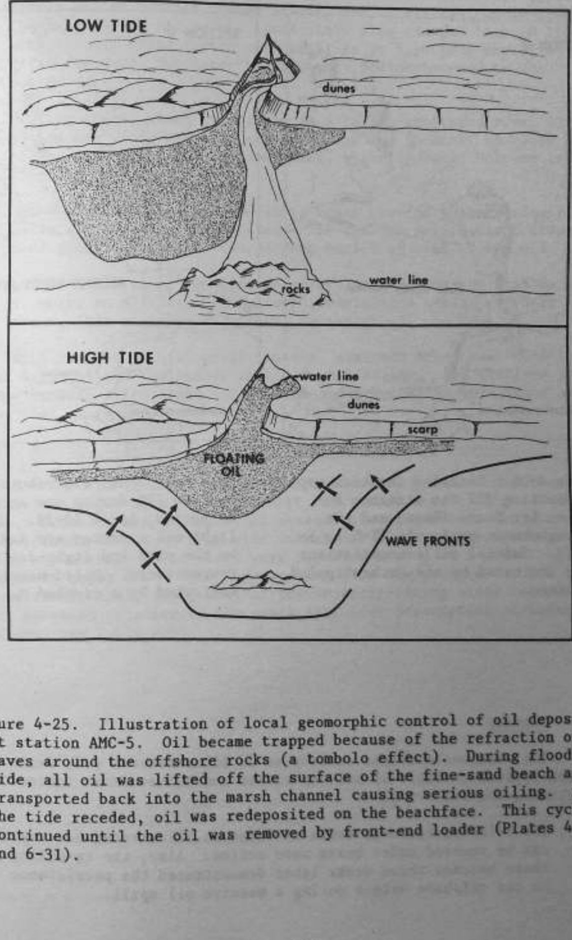


Figure 4-25. Illustration of local geomorphic control of oil deposition at station AMC-5. Oil became trapped because of the refraction of waves around the offshore rocks (a tombolo effect). During flood tide, all oil was lifted off the surface of the fine-sand beach and transported back into the marsh channel causing serious oiling. As the tide receded, oil was redeposited on the beachface. This cycle continued until the oil was removed by front-end loader (Plates 4-8 and 6-31).

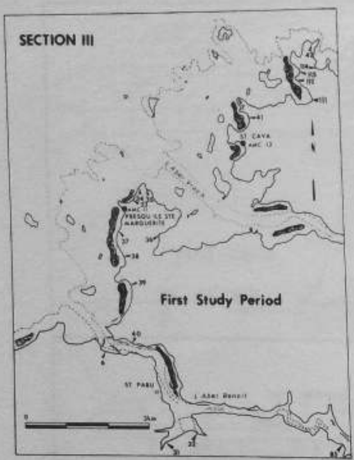


Figure 4-26. Detailed location map of Section III for stations between Les Dunes (East) and the Plouguerneau peninsula (F-6 to F-142). Initial oil concentrations are indicated by the dark-stippled pattern.

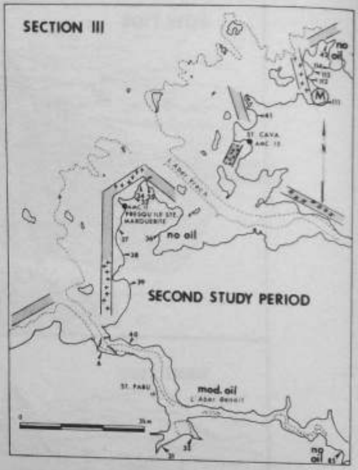


Figure 4-27. Oil distribution along Section III during our second study period, April 20-28. Heavy and light oil coverage are indicated by the plus and light-dot patterns, respectively. Oiled marshes are indicated by a circled M.

<u>Summary</u>

The stations surveyed in Section II illustrated a wide variety of morphological controls of oil deposition and oil-sediment interaction, including the following:

(1) The rocky environment south of Trémazan illustrated how rapidly oil can be removed under heavy wave action. Also, the re-oiling of these beaches three weeks later demonstrated the persistence of oil in the offshore waters during a massive oil spill.

(2) In the low-energy environment of the Portsall region, the upper levels of the beaches showed an increase of oiling through time. The behavior of oil on the tidal flats also changed through time, with the oil being lifted off the flats at high tide during the first few days, but later being partly sediment-bound to the bottom.

(3) Station AMC-4, which is located in a large, sheltered cove, illustrated how winds and coastal morphology can interact to cause heavy oiling on one side of the embayment, while opposite beaches remain clean.

(4) AMC-4 also illustrated a definite beach erosion phase during the early stages of oil inundation. The erosion period was followed by sand deposition, which caused deep burial of some of the oil.

(5) An illustration of the tombolo effect was provided by station AMC-5, where an oil mass became compartmentalized behind offshore rocks, thus escaping alongshore transport.

With respect to biological impacts, stations AMC-3 and AMC-4 had total kills of the indigenous amphipod populations. All stations contained heavily oiled algae. Dead fish and polychaetes were found on the tidal flat at Portsall.

4.9.3 <u>Section III--Les Dunes East to Plouguerneau Peninsula</u>

Section III includes two north-south trending bedrock headlands as well as two major rias, l'Aber Benoit and l'Aber Wrac'h (Figs. 4-26 and 4-27). Each ria was an important aquaculture area before the oil spill. The headlands have 1 to 2 km wide intertidal flats on the northwesterly-facing exposures. These flats were probably formed as a result of erosion by major storm waves approaching from the northwest. Oil impact was extremely heavy along most of the westerly-facing areas because of their position relative to the wreck site (for description of individual stations, see Table 4-5).

Table 4-5. Field observations of oil distribution at stations of Section III, Lés Dunes-East to the Plouguerneau peninsula.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-6	20 Mar	Ker-Vigorn Mouth of estuary.	Oil boom deployed - no oil at this time - to become heavily oiled starting 21 March.
F-31	26 Mar	Grand Moulin Western arm of l'Aber Benoit; tidal flat (mud) with rocks along shore.	Very light sheen.
F-32	26 Mar	Le Carpont Arm of l'Aber Benoit; tidal flat.	Heavily oiled.
F-85	31 Mar	Treglonou Large fine-grained tidal flats.	Heavily oiled along shoreline.
F-40	26 Mar	l'Aber Benoit Entrance to estuary.	Boom in place.
F-39	26 Mar	Prat Allan Arcuate cobble beach.	Heavily oiled with a large oil pool offshore.
F-38	26 Mar-	Presqu'ile Ste. Margarite Coarse-sand pocket beach.	-heavily oiled.
	22 Apr-		-oil burial 70 cm and 35 cm with light swashes on surfaces.
F-37	26 Mar	Presqu'ile Ste. Margarite Coarse-sand pocket beach.	Heavily oiled.
AMC-11	26 Mar-	les Dunes de Ste. Margarite Medium-sand pocket beach backed by eroding dune scarp.	-heavily oiled; extensive clean-up operation with manpower, front-end loaders, and backhoes.
	1 Apr-		-heavily oiled upper berm; front-end loader removing oiled sand.
	22 Apr-		-95% cleaned; some minor burial.
F-33	26 Mar	South of Penn Enez Sand pocket beach.	Heavily oiled.
F-34	26 Mar	Penn Enez Boulders in front of small scarp beach.	60 m - heavily oiled.
F-35	26 Mar	Penn Enez (East side) Small pocket beach.	Moderate oiling.
F-36	26 Mar	Poullac Harbor Wide exposed sand flat.	No oil.

Table 4-5 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
AMC-12	27 Mar-	St. Cava Coarse-sand beach with a medium-sand, very broad, low-tide terrace lying between two rocky headlands.	-very heavy oiling of beach and upper tidal flat; large kill of cockles.
	1 Apr-		-still heavily oiled beach; manual clean-up operation.
	23 Apr-		-beachface is oil-stained, but without significant accumulations; oil mixed 17 cm into the low-tide terrace by the heavy trucks; interstitial water still contaminated.
F-41	20 Mar-	Kervenny Brag Sand tidal flat abutting a seawall and rocks located in a large pocket cove.	-very light swashes.
	27 Mar-		-very heavily oiled; extensive clean-up operation underway.
	23 Apr-		-95% clean, but the tidal flat has been churned up by heavy equipment.
F-7	20 Mar-	Lilia Rocks with algae along a channel at tow tide.	-oil streaks on the water; very light oil on shore.
	1 Apr-		-light oil sheen on water; very light oil on shore.
	23 Apr-		-definite mousse zone on algae and rocks.
F-111	23 Apr	Kerjegu Small embayment off of a large sand flat.	Marsh in upper portion of embayment - lightly oiled; otherwise clean.
F-112	23 Apr	Kelerdut Large tidal flat embayment protected by island and rocks offshore.	Clean tidal flat, but badly oiled shoreline; oiled gravel is piled up to be removed.
F-113	23 Apr	Porz Guen Rocky headland with small harbor/embayment.	All of the rocks heavily oiled, especially the northern corner of the harbor; beachface is lightly oiled; clean-up operation previously removed much of the oiled algae.
F-42	27 Mar	Porz Guen Angular boulder beach.	Lightly oiled.
F-114	23 Apr	Porz Guen Sandy pocket beach protected by rocky headlands on the north and west.	No oil.

Oil Impact, l'Aber Benoit and l'Aber Wrac'h

No oil was visible in l'Aber Benoit during our first visit on March 20. A number of booms had been laid in preparation for the oil. However, during our flight on the next day, oil could definitely be seen entering the estuary through the booms (Plate 4-30). Later, oil coverage became very heavy along the edge of the estuary and on some surfaces of the fine-grained tidal flats.

L'Aber Benoit has been selected for special study by CNEXO-COB. Dr. Laurent D'Ozouville had prepared a preliminary report on their work, and has given us permission to include his results in this report. His report follows (translated by Jacqueline Michel):

Impact of Pollution by the Amoco Cadiz in l'Aber Benoit

L'Aber Benoit can be divided into three geomorphological units:

Part A: from the entrance of l'Aber Benoit to Loc Majan (Fig. 4-28A), a zone characterized by well-developed sand or pebble beaches.

Part B: from Loc Majan to Treglonou (Fig. 4-28B), a narrower zone with midflats flanking a rocky shore.

Part C: from the port of Treglonou to the head of l'Aber Benoit (Fig. 4-28C); this zone is dominated by marsh grasses which become more prevalent toward the head of the bay.

Oil Distribution in l'Aber Benoit

(1.1) Geographical distribution

Several aerial surveys (fixed wing and helicopter) allowed us to map the oiled zones in l'Aber Benoit. It appears that:

-past the port of Treglonou toward the head of l'Aber, little pollution occurs.

-between the entrance of l'Aber Benoit and the port of Treglonou, the orientation of the shoreline with regard to the winds and currents explains the geographical distribution of the oil and helps us understand why certain areas are less polluted.

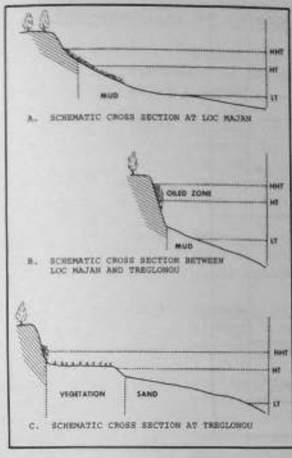


Figure 4-28. Oil distribution within l'Aber Benoit: (A) at Loc Majan, (B) Loc Majan to Treglonou, and (C) Treglonou to the head of the Aber (from preliminary report by D'Ozouville).

(1.2) Distribution with depth:

variable depending on the nature of the substrate.

-sand: penetration occurs but it is hard to say just how deep.

-mud: surficial, yet animal burrows permit some oil to penetrate.

-marsh grass: oil sits on the surface of the grasses which are covered only during high tides.

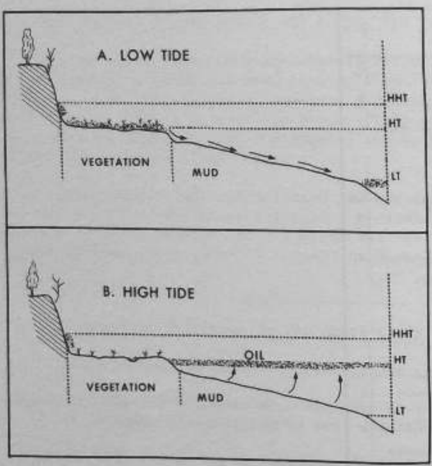


Figure 4-29. Oil reaction within l'Aber Benoit estuary during low and high tides. Much of the oil was resuspended off the flat as the tide flooded. (From a preliminary report by D'Ozouville.)

(1.3) Study of the pollution along transverse cross-sections (Fig. 4-29).

Oil which has accumulated in depressions in the rocks and grasses flows downhill on the surface of the mud during ebb tide. During flood tides, some oil is resuspended and slowly removed. It should be noted that a simple disturbance in the water causes the resuspension of bottom-held oil. It appears that the oil held in these depressions will have a long residence time in l'Aber Benoit.

Recommendation for Cleanup

Generally, it is necessary to prevent mechanical equipment on the polluted areas, and even more so on the marsh grasses.

(2.1) Upriver of the port of Treglonou--this area is covered by marsh grass and was not affected much by the oil. It is best not to attempt to clean this area except locally where the oil has accumulated in gaps in the marsh grass.

(2.2) Between Loc Majan and the port of Treglonou--this zone is primarily rocky, and is best cleaned by water spray and recovery of the oiled water.

(2.3) From Loc Majan to the mouth of l'Aber Benoit--cleanup consists of manual methods for the beaches and water spray for the rocks.

(2.4) Aerial observations showed that there were places of preferential oil accumulation (indicated on Figure 4-26). At these sites, with well-placed booms, oil could be accumulated rapidly and removed by pumps much more easily.

After these reflections, it seems to us indispensabe to continue the study of l'Aber Benoit. Through further study, we will gain a better understanding of the mechanisms of estuarine oil pollution and recovery. Also, the economics of the oyster fisheries make it essential to follow the de-contamination of the estuary in space and time.

Oil Impact on the Coast between F-36 and F-39

The area under discussion is the headland that separates l'Aber Benoit from l'Aber Wrac'h. Initially, oil accumulation was very heavy on the western side of the headland, while the eastern side (F-36) escaped oiling entirely (Fig. 4-26). As a result of the strong westerly winds, large oil pools formed at each indenture in the coastline. Station F-38 was particularly interesting in that it contained several thick layers of buried oil (Fig. 4-30), the deepest of which was 70 cm. This was the deepest burial observed during our study.

A detailed study was conducted at station AMC-11, a medium- to fine-sand pocket beach. A sketch of the area is provided in Figure 4-31. Sediment data are presented in Table 4-6. This area was selected because of its location with respect to the wreck site, the large amounts of oil present in the area, and because it had an ongoing cleanup operation.

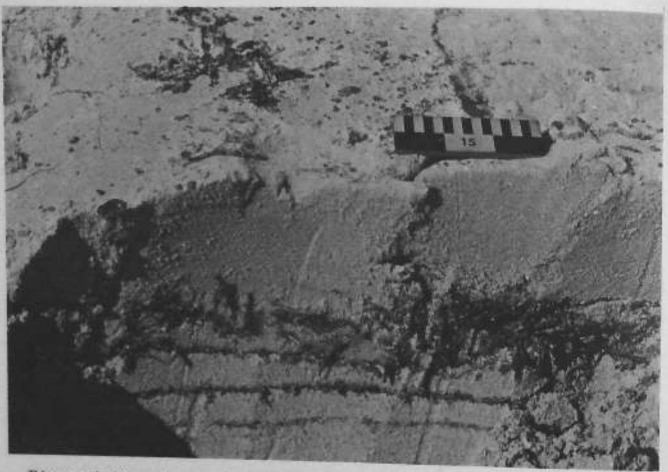


Figure 4-30. At station F-38 on April 22, we found buried oil, the deepest of which was 70 cm (not pictured). This was the deepest burial we observed at any site during the entire study. The sediment is composed of well sorted coarse-sand.

On March 26, oil covered the entire beachface and much of the fine-sand low-tide terrace (Fig. 4-31). We estimate that 175 tons of oil were present at that time (Table 4-6). In an attempt to remove the oil, a long trench was dug with a backhoe to collect the oil on the incoming and receding tides. The trench system was necessary to operate the suction hoses from tank trucks and honeywagons. Sand was taken from the base of the dune scarp to form a barrier to direct oil runoff into the trough.

Upon our return on April 1, some erosion had occurred at the upper beach face, possibly in response to the previous sand removal. As is shown in Figure 4-32, approximately 3 m of beach was lost. The upper 25 m of beach remained heavily oiled, up to 1.5 cm thick in some areas. A newly formed neap berm buried oil 5 cm below the surface. The lower part of the beach was clean, more likely due to wave and tidal current action than to mechanical cleanup. The trench that had been dug earlier was filled in. Unfortunately, the sand filling the trench was heavily mixed with oil. This oil could be the source of the noticeable ground water contamination in the area, and, hence, could have a long-term impact on the biological productivity of the area.

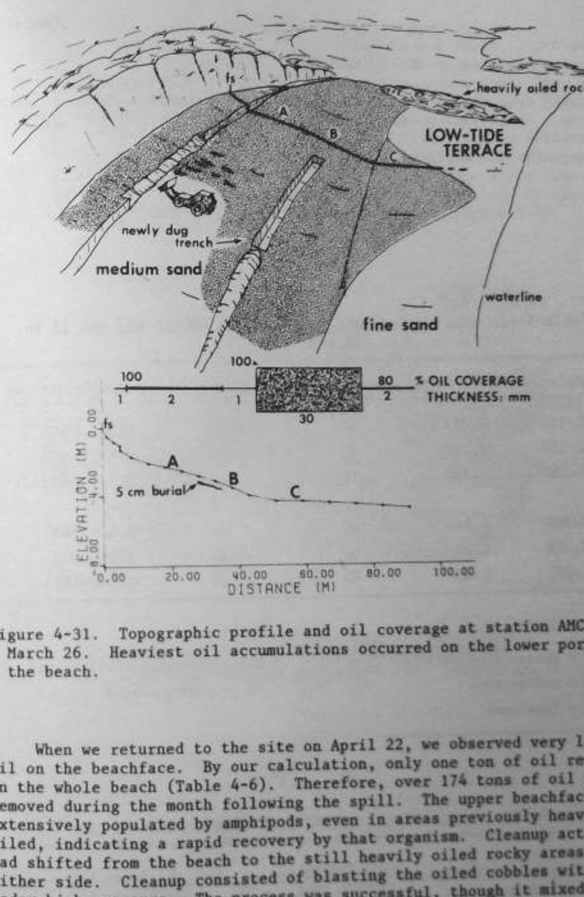


Figure 4-31. Topographic profile and oil coverage at station AMC-11 on March 26. Heaviest oil accumulations occurred on the lower portion of the beach.

When we returned to the site on April 22, we observed very little oil on the beachface. By our calculation, only one ton of oil remained on the whole beach (Table 4-6). Therefore, over 174 tons of oil was removed during the month following the spill. The upper beachface was extensively populated by amphipods, even in areas previously heavily oiled, indicating a rapid recovery by that organism. Cleanup activities had shifted from the beach to the still heavily oiled rocky areas on either side. Cleanup consisted of blasting the oiled cobbles with water under high pressure. The process was successful, though it mixed oil into the cleaner sediments on the beach, but was very time consuming. On the southern side, volunteers were scooping oil from between the boulders by hand.

Figure 4-32. About 3 m of beach erosion occurred at AMC-11 during the week after mechanical removal of sand from the base of the dune scarp. Deposition on the lower beachface caused oil to be buried 5 cm below the surface.

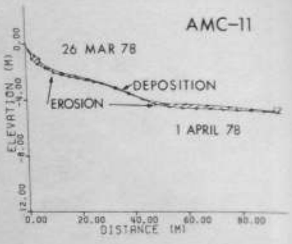


Table 4-6A. Grain size data for stations AMC-11 and AMC-12 in Section III.

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-11A	1.947	MS	-0.116	0.536 (MWS)
AMC-11B	2.124	FS	-0.059	0.639 (MWS)
AMC-11C	1.798	MS	-0.117	0.690 (MWS)
AMC-12A	0.533	CS	0.168	0.531 (MWS)
AMC-12B	0.106	CS	0.201	1.993 (PS)
AMC-12C	1.306	MS	-0.125	0.689 (MWS)

[1]Size Class

CS = coarse sand

MS = medium sand

FS = fine sand

[2]Sorting

MWS = moderately well sorted

PS = poorly sorted

Table 4-6B. Change in oil quantity at stations AMC-11 and AMC-12.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-11	26 Mar	175.2	22 Apr	1.0	-99.40
AMC-12	27 Mar	357.7	23 Apr	6.3	-98.30

Oil Impact on the Coast between AMC-12 and F-42

This west-facing shoreline (Fig. 4-26) was exposed to predominant wave and wind approach during the early days of the spill. The area between stations AMC-12 and F-7 was impacted by major concentrations of oil, whereas the more northerly stations received lesss.

Station AMC-12, which was studied in some detail, is a coarse-to medium-sand beach abutting an eroding, low-lying dune field (see Table 4-5 for sediment data). Rocky headlands flank both sides of the beach. A sketch and topographic profile are presented in Figure 4-33.

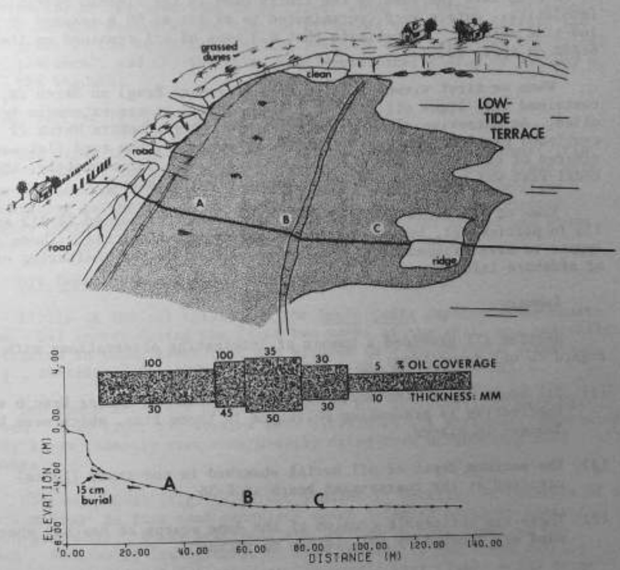


Figure 4-33. Topographic profile and oil coverage at station AMC-12 on March 27. The thickness of the oil coverage line is proportional to actual oil thickness. Heaviest accumulations occurred on the low-tide terrace in a low-relief runnel behind a ridge.

On the date of our first survey (March 27), the beachface at AMC-12 was entirely coated with oil, as was much of the low-tide terrace. Oil was ponded 4 cm thick in a runnel landward of a low-relief ridge on the low-tide terrace. Our estimates indicate that 358 metric tons of oil were present on the beach on March 27 (see Table 4-6)[7]. A large number of dead cockles (Cerastoderma) had accumulated along the step of the high-tide beachface (avg. of $6/m^2$; see Plate 4-25).

During our return visit on April 23, the beachface and low-tide terrace were cleared of massive quantities of oil; however, 70% of the beach sediments still appeared oil stained. Some slight burial (6 cm) was observed. The hard gravel and clay base that underlies the beach inhibited much oil penetration. On the low-tide terrace, oil was mixed 17 cm deep into the sand by the trucks used in the cleanup operation. Interstitial waters were contaminated to as far as 50 m seaward on the low-tide terrace. We estimate that 6.3 tons of oil remained on the beach on April 23.

When we first viewed station F-41 (Kervenny Brag) on March 20, it contained only light oil swashes. By March 27, it was extremely heavily oiled. An extensive cleanup operation which began before March 27 continued past our visit of April 1. By April 23, the sand flat was 95% cleared of oil. Only the seawalls retained oil. Unfortunately, the tidal flat was badly churned up by the cleanup machinery.

Some of the areas north of F-41 were moderately oiled (F-112 and F-113 in particular), but most areas only received light oil. These areas appear to have escaped major oil damage because of the sheltering effect of offshore islands.

Summary

Section III provided a number of interesting observations with regard to oil deposition:

(1) Oil booms across the mouth of l'Aber Benoit and l'Aber Wrac'h were ineffective in preventing pollution in those rias, which were badly damaged in places.

(2) The maximum depth of oil burial observed in the study (70 cm) occurred at the coarse-sand beach at F-38.

(3) There was noticeable erosion of the dune scarps at beaches where sand was removed by the cleanup operation.

[7] This is a revised value from our preliminary field report, in which we reported 538 tons on this beach.

(4) The trenching technique observed at AMC-11, while effective for cleanup, probably increases the pollution of the interstitial water of the beach.

(5) Oil deposition is closely controlled by local beach morphology, as was illustrated by oil accumulation in the runnel at AMC-12 (see Fig. 4-33).

(6) In general, most of the stations in this section located on the exposed headlands were remarkably clean one month after the spill, especially considering the large volumes of oil that came ashore during the first few days of the spill. The rapid natural cleaning of these areas is probably a function of the high degree of exposure of the headlands to northwest winds and waves. The general erosional nature of the area is evidenced by (a) the overall retreat of the shoreline (leaving behind a wide, wave-cut intertidal platform), and (b) the thin, non-depositional character of many of the beaches.

4.9.4 Section IV--Trouloc'h to Brignogan-Plage

The coastline of Section IV is oriented northeast-southwest (Fig. 4-34). Much of the coastline consists of depositional dune areas with granitic bedrock outcrops. An exception to this general shoreline orientation is the Neiz Vran peninsula (AMC-13), which is oriented roughly north-south. Table 4-7 gives brief descriptions of the study sites, and Table 4-8 presents sediment and oiling data.

Oil Impact

Little of the oil spilled by the Amoco Cadiz impacted this coastline. Oil impact during the first two weeks of the spill was generally restricted to those areas that are aligned in a north-south direction (e.g., stations F-44, AMC-13, F-48, and F-50; see Fig. 4-34).

One month after the spill, all major oil accumulations were dispersed. Only light oil swashes were visible at all stations. Sheltered rocky areas commonly were more heavily oiled than neighboring sand beaches.

Station AMC-13 (Fig. 4-34) was studied in detail. It consists of a small medium- to fine-sand crenulate beach oriented north-northeast/south-southwest. Rocky headlands are located on both sides of the beach. Because of its orientation with respect to the wreck site, a large quantity of oil estimated at 248 metric tons (Table 4-8B) accumulated during the first two weeks after the spill. During our first site visit on March 26 , most of the beachface and upper low-tide terrace was 100% oil covered. The topographic profile and oil coverage diagram are presented in Figure 4-35. Thick (30 cm) mixtures of mousse and algae accumulated at the upper portions of the beach and along the

Table 4-7. Field observations of oil distribution at stations of Section IV (Trouloc'h to Brignogan-Plage).

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-115	23 Apr	Penn ar Stréjou Small sandy pocket beach facing north; sandy dunes backing the beach; tidal flat in front of beach.	The beach contains some light oil swashes; rocky areas are moderately oiled; some of the algae is coated by a thick covering of mousse.
F 116	23 Apr	Corejou Neck of a peninsula, connects an island offshore; embayments north and south.	No oil on north side of jetty; lightly oiled cobbles on south side.
F-43	27 Mar- 23 Apr-	Mogueran An embayment with a large tidal flat (1-1½ km) in front; rocky on both sides with much rock debris on beach.	-clean; no oil. -some new oil has come onshore; very light, a mousse froth that is on the upper portions of the beach and is mixed in with the algae.
F-117	23 Apr	la Secherie Large sandy beach with sand dunes backing it.	Lightly oiled along the swash lines as well as on some of the rocks.
F-44	27 Mar- 23 Apr-	Le Curnic Contains a jetty separating two sandy beaches; much rock debris on the beaches.	-rocks on the jetty are lightly to moderately oiled. -light oiling of rocks on both sides of jetty; beaches clean except for light oil swash lines.
F-118	23 Apr	Lerret Near the head of a large estuary/tidal flat.	Marsh in the upper intertidal zone is moderately oiled; light oil swashes on sand leading down from oiled seawall.
F-119	23 Apr	Trésséňy Middle of a large estuary/tidal flat.	Lightly oiled rocks and seaweed swash line.
AMC-13	27 Mar- 23 Apr-	Roc'h Quelennec Medium- to fine-sand beach and tidal flat with rocky headlands on both sides; large boulders on beachface.	-very heavily oiled beachface; oil 30 cm thick, mixed with algae along upper swash zone. -surface 99% clean, but deep 38 cm burial along upper beachface; also has oil contaminated interstitial water.
F-45	27 Mar- 23 Apr-	Neiz Vran Mixed sand and rock debris beach with large tidal flat in front.	-no oil. -upper intertidal algae and seaweed lightly oiled.
F-46	27 Mar	Boutrouille Well-sorted granule beach	Very light oil swashes.
F-120	23 Apr	(near) Louc'h an Dreff Coarse-grained beach with a fine-sand low-tide terrace.	Clean except for a few minor oiled swash lines.
F-47	27 Mar	(near) Kerlouarn Steep, mixed-sand and granule beach.	Lightly oiled rocks.

Table 4-7 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
AMC-14	27 Mar- 23 Apr-	Kerlouarn Sheltered, grassed, embayment used as a small harbor.	-5 m wide heavily oiled grasses. -a dirt road constructed over oiled swash.
F-48	27 Mar- 23 Apr-	Carrec zu Sandy beach with large dune system; relict marsh outcropping on beach - therefore, an erosional beach.	-light oil swashes. -clean sand with light oil swashes.
F-49	27 Mar	(near) Chapelle Pol Sandy beach with large dune system; some rocks and rock debris scattered along beach.	Heavily oiled rocks.
F-50	28 Mar- 23 Apr-	Lighthouse at Pointe de Beg Pol Rocky point sticking out with sandy beaches on both sides.	-heavy oiling on both rocks and beaches. -sand tinted brown, but now only lightly oiled; rocks also oiled lightly.
F-121	23 Apr	Kervernen Rocky beach with some sand underneath.	Sand is clean, but rocks are lightly to moderately covered with oil; some algae is clinging to rocks and surviving the oil coverage.
F-122a	23 Apr	Brignogan Plage Large harbor tidal flat.	Light oil swashes; light oil on algae; some of the rocks are dark from light oil staining.

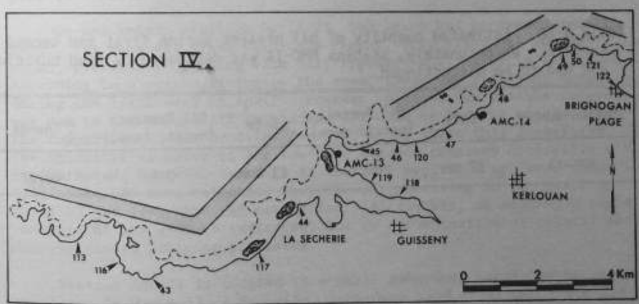


Figure 4-34. Locations of stations in Section IV, from Trouloc'h to Brignogan-Plage. Initial oil depositon was generally limited to those areas trending perpendicular (north/south) to overall oil transport. Initial oil depositon is indicated by the dark-stippled pattern. Oil coverage during our second study period (April 20-28) was light in all areas (indicated by the light-dot pattern).

Table 4-8A. Grain size data for AMC stations 13 and 14 located in Section IV of the survey area.

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-13A	1.824	MS	0.116	0.640 (MWS)
AMC-13B	2.400	FS	-0.409	0.948 (MS)
AMC-13C	2.348	FS	-0.367	1.016 (PS)
AMC-14	1.468	MS	-0.245	1.210 (PS)

[1]Size Class

MS = medium sand
FS = fine sand

[2]Sorting

MWS = moderately well sorted
MS = moderately sorted
PS = poorly sorted

Table 4-8B. Estimated quantity of oil present during first and second surveys. Unfortunately, station AMC-14 was destroyed by road building and had to be discontinued.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-13	27 Mar	248.3	23 Apr	0.6	99.97

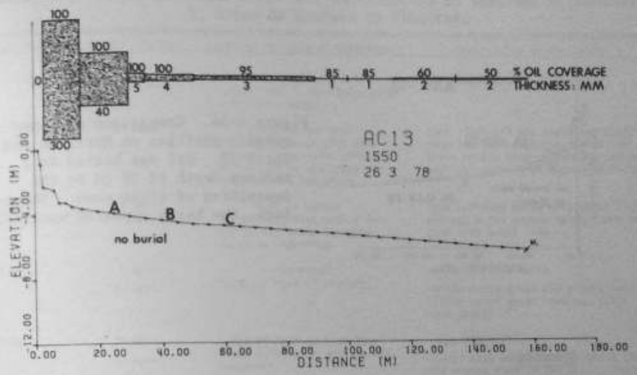


Figure 4-35. Topographic profile and oil coverage at station AMC-13 on March 26. Thick oil and algae were found along the upper beach face.

joint pattern of the rocks (see Plate 4-17). Around some of the large boulders on the beach, thick oil accumulations collected in the scour pits (see Plate 4-16).

On our return visit on April 23, the beach had recovered remarkably. The sand was clean with only recent, very light oil swashes. The rocks, previously dripping with oil, appeared only slightly blackened. According to a person living in the area, there was a cleanup operation during the first week in April. However, part of the visible recovery was due to the burial (38 cm maximum) of some of the oil by new sand. The comparison of our profiles (in Fig. 4-36) shows this deposition. The interstitial water of the low-tide terrace remained noticeably oil contaminated; however, castings of the worm Arenicola sp. were found in abundance. We have estimated that the oil remaining on the beach on April 23 was less than one metric ton. Altogether, an amazingly rapid recovery of the area is indicated, due to a combination of natural and man-engineered cleaning processes.

Station AMC-14 is located in a small embayment populated by marsh grasses. On March 27, a 5-m-wide, 3-cm-deep band of mousse froth had been deposited on the grass. However, by April 23, a dirt road had been constructed over the oil, thereby destroying its value as a study area.

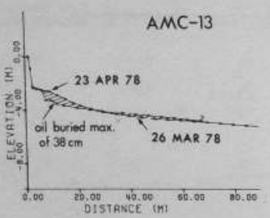


Figure 4-36. Comparison of topographic profiles on March 26 and April 23. Oil was buried to a maximum depth of 38 cm by the deposition of clean sand. Therefore, the beach appeared unoiled.

<u>Summary</u>

Section IV illustrates the following points:

(1) There was a lack of significant oil deposition along those stretches of coast oriented NE-SW, which were at an angle of 45° to the primary oil transport direction. All areas trending roughly north-south (perpendicular to oil transport) were heavily impacted (particularly station AMC-14).

(2) The burial of an oil layer by up to 38 cm of new sand at AMC-14 gave the beach a deceptively clean appearance on 23 April.

(3) Oil was observed to accumulate in pools in scour pits around boulders at station AMC-14.

4.9.5 <u>Section V--Grève de Goulven to Plougoulm</u>

Section V can be divided roughly into two sections, a depositional section to the west, and an eroding granitic bedrock massif to the east (Fig. 4-37). The depositional system is composed of an extensive dune area and very wide fine-sand tidal flat (Grève de Goulven). Beaches within the bedrock area are usually small and bounded by rocks. Most of the oil passed by this coast. However, there were significant accumulations during the first two weeks in those areas jutting north into the channel, and those that had coves or crenulate features facing west. A brief description of the individual study sites is presented in Table 4-9.

Table 4-9. Field observations of oil distribution at stations of Section V, Grève de Goulven to Plouscat.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-122b	23 Apr	Gourven Large tidal flat/estuary with a fringing marsh.	Very lightly oiled marsh grass.
F-123	23 Apr	Plage de Ker Emma Wide sandy beach with dune system; large rocks offshore as well as on the lower portions of the beachface.	Some light oil and small tar balls aong the last high tide swash line. Fresh mousse (moderate-heavy concentration) coating on algae and rocks.
F-124	23 Apr	Anse de Kernic Large tidal flat with a harbor on one side; fringing marsh on shoreline.	Some darkened marsh grass from light oiling; a few mousse balls along the high tide swash line.
F-86	1 Apr- 23 Apr-	Plouescat Marsh at head of estuary.	-heavily oiled marsh -oiled marsh grass all ripped out; little marsh grass remains; still some patchy oil.
F-30	25 Mar- 23 Apr-	End of Spit at Porz Meur Beach with rocky area to the southwest.	-very light oil. -rocky area moderately oiled; a little mousse foam in the water; light oil swashes on the last high tide line.
F-29	25 Mar- 23 Apr-	Por au-Streat Breakwater harbor with seawall protecting it from direct wave attack.	-beach heavily oiled; lots of clean-up activity. -just a little oil on beach with some burial along the upper swash line. The rocks are all lightly oiled.
F-28	25 Mar	Frouden Rocky cobble beach with some sandy areas.	Oil pools; clean-up operation in effect.
F-27	25 Mar	(near) Au Gered Pocket beach.	Heavily oiled gravel beach and rocks.
F-26	25 Mar	Point at St. Eden Pocket sand beach with rocky headland on both sides.	Heavily oiled rip-rap seawall.
F-25	25 Mar- 23 Apr-	Pornejen High energy boulder beach.	-heavily oiled rocks; 200 m slick of mousse. -light oil coverage on rocks; much of the oil on rocks removed by high pressure hoses.
F-24	25 Mar	Poulfuen Pocket beach with rocks on sides.	Heavily oiled.
F-23	25 Mar- 23 Apr-	Kerfissien Small pocket beach with rocks on sides.	-moderately oiled especially in the eastern zone. -beachface was clean with half-buried, discontinuous mottled oil zone along the swash zone and a few buried tar balls at 50-60 cm.
F-22	25 Mar- 23 Apr-	Anameid High-energy beach with eroding dune scarp and rocky headlands on both sides of a small embayment.	-beach is heavily oiled; heavy mousse swash. -area entirely clean.
F-21	25 Mar	Tavenn Kerbrat Sandy beach with heavy rock debris.	Very light mousse in water.

Table 4-9 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-57	28 Mar- 26 Apr-	Plage de Trestrignel Sandy shoreline with some rocks sticking thru a muddy sand flat at the center of the tidal channel.	-light sheen in water. -light oil swash lines along the upper part of the shore; oil burial 6-8 cm on the upper portion of the beachface; live amphipods found along the high tide swash.
F-87	1 Apr	Kerbrat Side of estuary.	Lightly oiled.
F-136	26 Apr	Kerbrat Fine- to medium-sand tidal flat	Very light oil swash along the high tide swash line; no oil burial; live amphipods on the beach.
F-137	26 Apr	Cantel Marsh area at the mouth of an estuary.	Marsh heavily oiled with 1 cm thick coverage of oil over marsh; no clean-up operation.
F-138	26 Apr	Traon Feunteun Upper portion of marsh where channel flows into the marsh.	Very lightly oiled; boom ineffectively positioned.

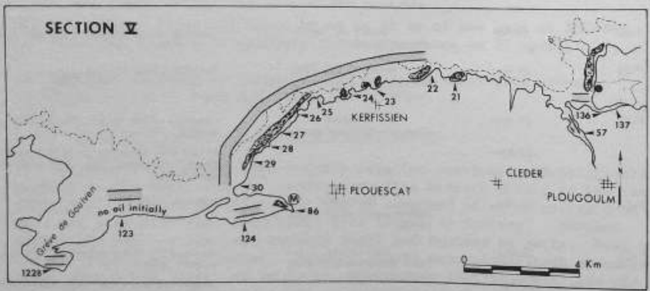


Figure 4-37. Station locations and oil distribution for Section V (Grève de Goulven to Plougoulm). Oil distribution for the first (March 19 to April 2) and second (April 20-28) study periods is indicated.

Oil Impact

The nature of oil deposition was distinctly different in the two morphological areas. Because the entire depositional system was sheltered by the Brignogan-Plage peninsula of Section IV, no oil reached the beaches during March. On our return visit during mid-April, light oil swashes were present on all beaches but no oil burial was found.

Beaches of the granitic massif were more exposed to the wind-transported oil; however, most of the oil simply passed by this area because of the general northeast/southwest orientation of the coast and the lack of large catchment areas. Significant amounts of oil accumulated only in those areas with crenulate shapes (crenulate beaches) or on those areas oriented more directly into the westerly winds (see Fig. 4-37). Commonly, the northern end of the beach would be heavily oiled, whereas the southern end would be clean.

During our site survey of late April, only a very light oil swash was visible at most locations. Cleanup occurred rapidly because of the exposure of most of the oiled areas to high wave energy. The exceptions were the sheltered marsh environments, such as the one at Cantel (F-170).

Summary

Importantly, Section V illustrates the change in form that the oil spill took after a period of one month. Originally, large oil masses were trapped at specific locations, depending on local shoreline configuration with respect to the wind. As the oil became worked into the water column, and the winds shifted, oil was spread over almost every inch of the shoreline in the form of light oil swash lines, which were usually composed of very small mousse balls.

Figure 4-38. Station locations and oil distribution for Section VI (Forêt Dom. de Santec to Roscoff). Oil distribution for period one (March 19 to April 2) is indicated by the dark-stippled pattern. Heavy and light oil coverage during period two (April 20-28) are indicated by the plus and light-dot patterns, respectively.

4.9.6 Section VI--Forêt Dom. de Santec to Roscoff

Geomorphologically, this section can be divided into two distinct areas: (1) a large relict dune field with broad, flat fine-sand beaches (between stations AMC-10 and F-17; see Fig. 4-38); and (2) the highly embayed area around Roscoff. All the fine-sand beaches of the first area were heavily contaminated because of their north-south orientation and generally crenulate shape. Roscoff was one of the hardest hit areas in the whole spill site during the first week after the spill and, therefore, was studied more intensely than some of the other areas. Summaries of field observations in section VI are listed in Table 4-10.

Table 4-10. Field observations of oil distribution at stations of Section VI (Forêt Dom. de Santec to Roscoff).

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
AMC-10	24 Mar (F)- 25 Mar (AMC)-	Forêt Dom. de Santec Eroding dune scarp with wide fine-sand beach grading into a broad low-tide terrace.	-contains a 20 m band of oil along the upper beachface; 12 cm burial.
	1 Apr-		-light oil swashes on beach surface; a discontinuous layer buried 8 cm.
	26 Apr-		-very light oil swashes on beach surface; discontinuous layer buried a maximum of 23 cm.
F-20	24 Mar- 25 Mar-	Dossen Wide fine-sand beach/low-tide terrace behind an island.	-tombolo effect; heavy oiling of entire area behind island.
	1 Apr-		-surface of low-tide terrace clean; oiled rocks along shoreline; signs of a clean-up operation.
	26 Apr-		-rocks still moderately to heavily oiled; some burial 10-12 cm along upper beachface.
F-19	24 Mar-	Port au Vil Small pocket sand beach	-very heavily oiled.
	26 Apr-		-clean beach surface and rip-rap, but 12 cm burial of 4 cm thick oil layer by spring berm deposition; signs of clean-up operation.
F-18	24 Mar-	Tevenn Large sand beach oriented into direct wave attack; has a marsh deposit outcropping on the beachface.	-very heavily oiled.
	26 Apr-		-oil well mixed into the beachface by heavy machinery and trenches used in clean-up operation; men working to spray clean rocks to south.
AMC-9	24 Mar (F)- 25 Mar	Cough ar Zac'h Broad medium- to fine-sand beach backed by eroding dune scarp; some rip-rap.	-very heavily oiled beachface and upper low-tide terrace; 8 cm burial along upper beachface.
	1 Apr-		-heavy oiling restricted to 12 m along upper beachface; 8 cm burial.
	26 Apr-		-only light swashes along beachface; burial to 25 cm; clean-up by raking.
F-17	24 Mar-	Centre Helio-Marin Wide fine-sand beach backed by eroding dunes.	-very heavy oiling of the entire beachface.
	26 Apr-		-no oil on beach surface or buried, but has oiled interstitial water; evidence of mechanical clean-up effort.
F-139	26 Apr	Ruguel Large sand flat with seawall.	Light oil swashes and lightly oiled rocks.
F-140	26 Apr	Lagadenou Small beach with seawall fronting a large sand flat.	Very heavily oiled during March; now has buried oil (3 layers) along beachface; tidal flat still oiled and has oil contaminated ground water.
AMC-8	24 Mar (F)-	Roscoff - West Small mixed-sand and gravel beach leading onto a very broad sand flat with some algae coated rocks; seawall and park back the beach.	-heavy oil coverage of beach, tidal flat and seawall; oil thrown over seawall and into park; oil boom in place across sand flat.
	25 Mar-		-decreased amount of oil on the tidal flat; the rest was the same.
	1 Apr-		-very light oiling on the beach; oil buried under 20 cm of cobbles; park heavily oiled, but walkway clean.
	26 Apr-		-oil stained cobbles and wall, but beach appears clean; park is replanted.

Table 4-10 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
AMC-7	24 Mar-	Roscoff - central harbor Small medium-sand beach between rocks on both sides; backed by a seawall.	-pooled oil 6 cm deep by seawall; rest of beach 70-90% oil covered.
	25 Mar-		-an approximate 70% reduction in oil coverage.
	1 Apr-		-some oil-bound sediment on low-tide terrace; oily sheen present; beachface clean; cleaning wall with detergents.
	26 Apr-		-clean beachface; very minor amount of oil buried at 22 cm.
AMC-6	24 Mar-	Roscoff - East Small coarse-sand and gravel beach grading onto a fine-sand tidal flat, rocks are found on both sides; seawall abuts the shore.	-the entire beachface and low-tide terrace had 35-100% oil coverage.
	25 Mar (F)-		-total oil coverage decreased to approximately 20%.
	1 Apr-		-beachface very lightly oiled; seawall and rocks on tidal flat still oil blackened; oil contaminated interstitial water.
	26 Apr-		-still lightly oiled rocks and seawall; cobbles of beachface are oil stained; interstitial water still contaminated.

Oil Impact in Western and Central Areas

Station AMC-10. This station, which is located at Forêt Dom. de Santec, is a very broad fine-sand beach backed by an eroding dune scarp. The total length of beach is 1250 m. A sketch of the area on March 25 is presented in Figure 4-39. Sediment data are listed in Table 4-11. During our site visits on March 24 and 25, oil was deposited along the uppermost 20 m of beachface. Because of the compact nature of the fine-grained sediments, heaviest accumulations occurred along the upper swash zone. The quantity of oil present determined the total amount of surface area coverage. Some burial of oil was observed (see Fig. 4-39), illustrating that minor deposition had occurred since oil first came onshore. The quantity of oil present along this beach was estimated at 446 metric tons (Table 4-12).

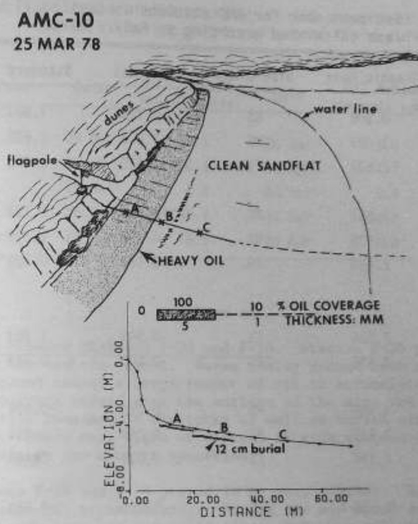


Figure 4-39. Sketch and topographic profile for station AMC-10 on March 25. All oil deposition was along the upper beach face. The total width of oil deposition on similar fine-sand beaches depends on the total quantity of oil within the area. Greater quantities will cover more of the beach face. Two distinct oil layers were buried, illustrating deposition of new sand since initial oil impact.

On our follow-up survey of April 26, only lightly oiled seaweed debris, and a series of light oil swashes remained on the beach surface. A 5-cm-thick oil/sediment layer was buried 10 to 15 cm below the surface by a newly formed berm. This recent deposition of clean sand gave the beach the appearance of being completely unoiled. We estimated that 6 tons of oil remained in the area, a net decrease of 87%. Approximately half of this oil was buried.

Table 4-11. Sediment data for AMC stations in Section VI. All values are calculated according to Folk (1968).

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-6A	0.306	CS	-0.129	1.601 (PS)
AMC-6B	1.007	MS	-0.813	2.670 (VPS)
AMC-6C	2.597	FS	-0.678	1.275 (PS)
AMC-7A	1.887	MS	-0.291	0.733 (MS)
AMC-7B	1.538	MS	-0.393	1.339 (PS)
AMC-7C	2.495	FS	-0.161	0.901 (MS)
AMC-8A		no sample		
AMC-8B	2.536	FS	-0.545	1.103 (PS)
AMC-8C	2.158	FS	-0.235	0.728 (MS)
AMC-9A	1.959	MS	0.010	0.434 (WS)
AMC-9B	2.112	FS	-0.049	0.459 (WS)
AMC-9C	2.197	FS	-0.011	0.486 (WS)
AMC-10A	2.955	FS	-0.095	0.358 (WS)
AMC-10B	3.005	VFS	-0.093	0.389 (WS)
AMC-10C	3.017	VFS	-0.123	0.419 (WS)

[1]Size Class

CS = coarse sand
MS = medium sand
FS = fine sand
VFS = very fine sand

[2]Sorting

WS = well sorted
MS = moderately sorted
PS = poorly sorted
VPS = very poorly sorted

Table 4-12. Estimates of the quantity of oil present at AMC stations in Section VI during first and second field surveys.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-6	24 Mar	51.8	26 Apr	1.0	-98.10
AMC-7	24 Mar	102.5	26 Apr	1.7	-98.30
AMC-8	25 Mar	9.6	26 Apr	0.4	-96.50
AMC-9	25 Mar	1039.4	26 Apr	10.6	-99.00
AMC-10	25 Mar	46.3	26 Apr	6.0	-87.00

Coast between Stations F-20 and F-18. Station F-20 provided another example of the tombolo effect. Waves coming around both sides of the offshore island caused a large amount of oil to accumulate at Dossen. Follow-up surveys showed that the surface of the area was cleaned, but some oil still remained on the rocks as well as buried along the upper beach face. There were signs of cleanup at each station (F-18, 19 and 20); however, we saw none in operation.

Stations F-19 and F-18 proved to be very similar. Each initially had very large oil accumulations. During the mid-April survey, the surface of each area was generally clean, but some oil was buried. Station F-18 remained slightly more oiled than the other.

Station AMC-9. This station is a 2.0 km long, very broad medium-to-fine-sand beach. Sediment data are presented in Table 4-11. As at Station AMC-10, the beach area is backed by an extensive dune field. The waves are eroding the dunes at high tide forming a steep scarp. A sketch and topographic profile of the area are presented in Figure 4-40.

At the time of our survey on March 25, much of the beach face and low-tide terrace were covered with oil. Thickness of the oil varied from 6 m along the mid-beachface to 3 mm along the low-tide terrace. There was some oil burial along the upper beach face. An estimated total of 1039 metric tons of oil was on the beach on March 25.

By April 1, heavy oiling was restricted to the uppermost 12 m of beach. Oil thickness varied from 2 cm to 3 mm. Oil was found buried in a discontinuous layer 10 to 15 cm below the surface (Plate 4-26). Natural processes were responsible for the cleansing of the lower beach-face, since there had been no signs of beach cleanup effort.

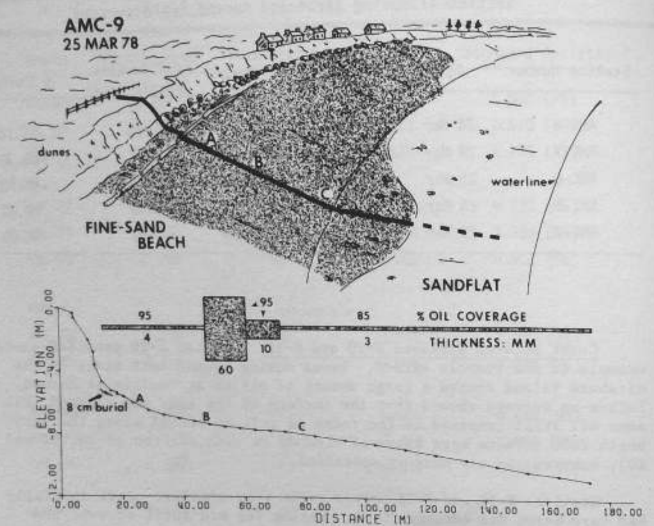


Figure 4-40. Topographic profile and oil coverage of Station AMC-9 on March 25. Oil covered most of the beach face and upper low-tide terrace. The profile is compressed, compared with the computer plot.

On April 25, only light oil swashes remained on the beachface. However, a good deal of oil was buried in two layers up to 25 cm deep. Comparison of beach profiles show that the formation of a neap berm caused the burial of the oil (Fig. 4-41). The rip-rap wall to the south continued to be heavily oiled. An estimated 11 metric tons of oil remained in the area. This comparatively large amount of oil is essentially due to the exceptional length of the beach over which the calculation was made.

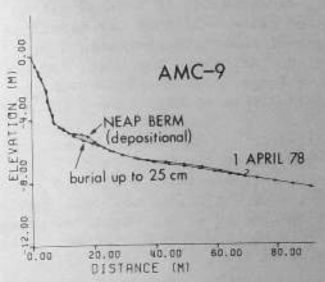


Figure 4-41. Although the beach at AMC-9 appeared clean on April 1, oil had been buried in two layers beneath the surface by formation of the neap berm.

The coast from F-17 to F-140. Station F-17 was very similar to the others of this coastline (e.g., AMC-10, F-18 and AMC-9). Backed by a small dune field, it contains a broad fine-sand beach and low-tide terrace. This area was initially very heavily oiled. Plate 4-10 shows this area on March 21. On April 26, little evidence could be found to indicate how extremely contaminated this area had been.

Station F-139 is located in a sheltered sand-flat embayment. Because of the prevailing westerlies during the first two weeks of the spill, no oil came into this area. During our second site inspection on April 26, minor oil swashes were found along the upper portions of the sandflat, and the rocks were lightly oiled.

Across the bay at site F-140, it was a different situation. This area was very heavily oiled during the first days of the spill. Skimmers and tank trucks worked to remove some of the floating oil. During site inspection on April 26, we found several layers of oil buried in the beach, and a surface film of oil on the sand flat. The interstitial water of the flat was noticeably contaminated.

Oil Impact in the Roscoff Area

Station AMC-8. This station is located on the west side of Roscoff. It consists of a steeply dipping mixed coarse-sand-and-gravel beach leading onto a sandy tidal flat. Grain size data are presented in Table 4-11. Behind the beach is a large seawall with a small park located at street level. We observed that the beach and most of the sand flat were oil covered during the flight of March 21 (see Plate 4-32). Our station is located along the seawall at the upper right of this photograph.

By March 25, much of the oil on the tidal flat was gone. However, the lower beach face remained oiled. An estimated 10 tons of oil remained (Table 4-12). Figure 4-42 and Plate 4-33 show the extent of the surface oiling. A hard, sandy gravel substrate prevented deep penetration of the oil. The walkway and park above the beach had received heavy oiling due to overwash by large, mousse-laden waves on March 24. Over 3 cm of oil was on the walkway at that time (Fig. 4-43).

By the first of April, little oil remained on the beach face. A minor amount was found buried by pebbles along the upper beach face. The walkway was cleared of oil, but the park was still blackened. By April 25, the park had been restored. Only the lightly stained cobbles and blackened sea wall (which was being cleaned with pressurized steam) remained as evidence of the spill. We estimated that less than 0.4 ton of oil remained in this particular area on April 25(Table 4-12).

Station AMC-7. This station is located within the jetties at Roscoff harbor (Fig. 4-44). The site is pictured in the background of Plate 5-17A. It is a small medium-sand beach bounded on both sides by large rocks. A fine-sand tidal flat is located seaward of the beach, while in back is a high seawall. Sediment data are presented in Table 4-11.

Our observations indicate that the heaviest accumulations of mousse arrived in Roscoff on March 20. On March 24, there was heavy oil coverage over most of the intertidal area at low tide (see our survey of that day, Fig. 4-45). Only where the ground water rills cropped out on the beachface did oil coverage reduce (to 70%). Some oil was also found buried. Returning the next day (two tidal cycles later), 60%-70% of the oil in the area had been removed. Comparing the two beach profiles presented in Figure 4-46, it can be seen that a large amount of material had been eroded from the beachface. In total, 23 m^3 of sediment per 1 m width of beach had been removed during the night. High wave activity brought about by a low pressure storm and near spring tides combined to create the new beach profile.

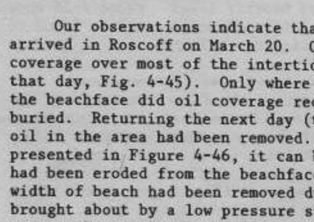


Figure 4-42. Topographic profile and oil coverage for station AMC-8 on March 25. The beach is composed of mixed sand and gravel leading onto a large sand flat.

Figure 4-43. More than 3 cm of oil was thrown up onto the walkway at station AMC-8 in Roscoff on March 24. The small part to the right was also heavily oiled. Most of the oil was cleaned up before April 1. The park was restored a short time after.

Figure 4-44. Aerial photograph of the harbor at Roscoff on March 21. Station AMC-7 is the beach to the center-left of the photograph. Station AMC-6 is located at the far left.

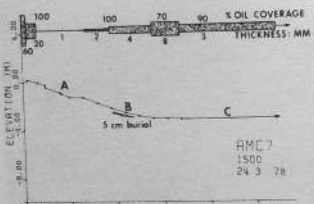


Figure 4-45. Topographic profile and oil coverage for station AMC-7 in Roscoff on March 24. A significant portion of the oil was removed by erosion of the beach during the following two tidal cycles (see Fig. 4-46).

On our return on April 1, we found that the entire beachface was clean. However, there was some burial of oil on the lower beachface (to depths of 3 cm). By comparing profiles (Fig. 4-46), it can be shown that new sand had been deposited between March 23 and April 3, thereby burying some of the oil. In total, nearly 30% of the original volume of sediment previously lost had been returned.

By April 26, only very light oil swashes were found on the beach. In addition, slightly oiled sediment was found 22 cm below the beach surface in one locality. The walls had been cleaned in some spots. The remaining oiled rocks and walls were being cleaned with high pressure water and detergents. This is the only place where we saw detergents applied to any oiled area. The total amount of oil present on April 26 was estimated at 1.7 tons (Table 4-12).

Another cleanup instrument, a vortex skimmer, was moored at this locality, but was seen being towed only once, and then it did not have the hoses connected for actual operation.

Station AMC-6. This station is located on the eastern side of Roscoff next to the lobster pens shown in Plate 5-17A. It consists of a small, 150 m gravelly sand beach that grades into a fine-sand low-tide terrace. Rocks are located on both sides of the beach. A seawall abuts the upper beach (see Fig. 4-47).

The oil pollution history of this area is very similar to that of AMC-7. During our overflight on March 21, the entire intertidal zone was covered with oil (Plate 5-17A). At the time of our survey on March 24, a considerable amount of oil remained on the beach face and low-tide terrace. Figure 4-47 shows oil coverage superimposed on the beach profile. We estimate that 52 metric tons of oil were present, excluding oil within the rocky areas. After a storm on the night of March 24, approximately 80% of the surface oil was removed. Once the oil drifted into the main channel, swift currents, aided by strong winds, carried it further to the east, towards Ile Grande.

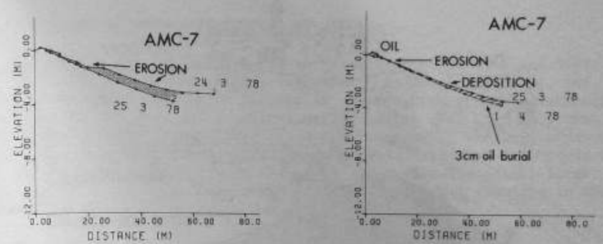


Figure 4-46. Extensive erosion occurred at station AMC-7 during the night of March 24. During this time, 60%-70% of the oil in the area was removed. The partial recovery of the beach on April 1, by the deposition of new sand on the beachface, caused a 3 cm burial of old oil.

A follow-up survey on April 1 showed a further diminution of the oil. On April 26, the beach still remained lightly oiled and the rocks and sea wall were still oil-blackened. The interstitial water was also contaminated. Approximately 1 metric ton of oil was still in this particular area on April 26. Limpets on the rocks seemed to be healthy, illustrated by their being able to hold firmly to the rocks when prodded.

Summary

(1) Exposed fine-sand beaches were cleaned rather rapidly (2-3 weeks) by natural processes. Only where oil was artificially worked deep into the beach sediments by cleanup machinery, did major contamination remain.

(2) Another example of the tombolo effect on oil accumulation was observed at station F-20 (Dossen).

(3) Tremendous quantities of oil were removed from the beaches of Roscoff overnight during a period of high wave intensity (March 24 and 25). Even though the large majority of oil was removed naturally, total recovery of the environment at Roscoff still seems somewhat distant. Oil that was naturally removed probably drifted eastward and contaminated other environments to the east.

(4) The use of sprayed detergents to clean the rocks at AMC-7 was the only use of chemicals we saw during our field studies.

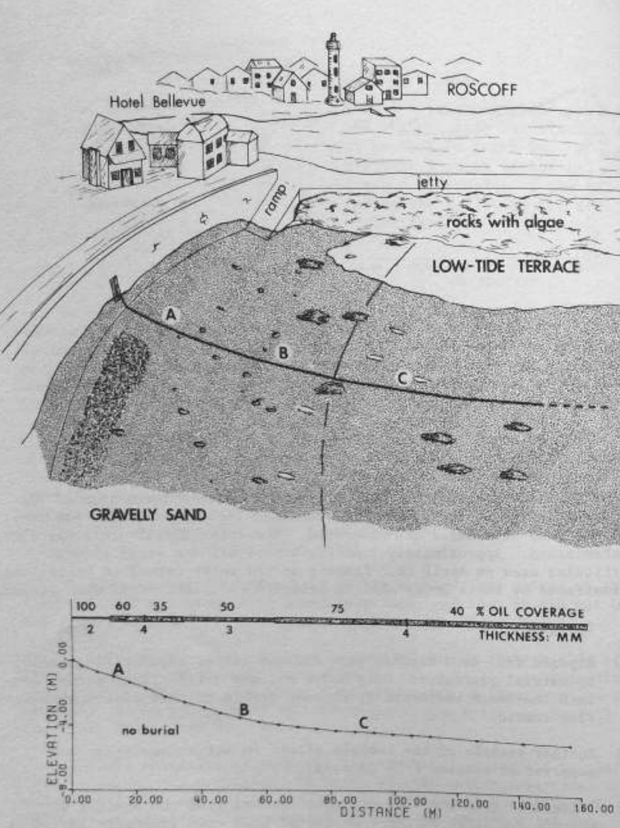


Figure 4-47. Sketch, topographic profile, and oil coverage for station AMC-6 in Roscoff on March 24. On the evening of March 24 approximately 80% of the accumulated oil was removed from the area by natural processes.

4.9.7 Section VII--Roscoff to Pte. de Plestin

A location map for Section VII is given in Figures 4-48 and 4-49. The coastline is oriented roughly east-west. Geomorphologically, the coastline is quite similar to Section IV, with a depositional, estuarine (ria) area to the west and a granite massif to the east. In this case, there are two large fine-grained tidal flat systems in the west separated by a bedrock headland, Locquirec peninsula. Another difference is that this bedrock area (between Locquirec and Primel-Trégastel) forms steep cliffs often over 20 m in height. The individual stations in the section are described in Table 4-13.

Oil Impact

The coast from F-147 to F-96. This entire section of coastline was sheltered from initial oiling by the Roscoff peninsula. No oil was found in this area during our first survey, which ended on April 2. There was a very long floating oil boom located across the eastern side of the estuary at this time (indicated in Fig. 4-48). The effectiveness of the boom could not be determined.

Since much of the large oil pools had shifted location with the changing wind direction of early April, we remonitored the area on April 27 in greater detail than before. During this survey, light oil swash lines were found at stations F-147, F-13, F-11, and F-96 (see Fig. 4-49). The rest of the area continued to be unoiled.

The coast from F-96 to F-89. This area was more exposed to the oil drifting over from Roscoff in the early days of the spill. Many areas became heavily oiled. Stations F-94 and F-95 were among the hardest hit. The latter consists of a large heavily oiled cobble beach. Because oil sank deep into the sediments, tractors and high pressure hoses were being used to clean the area. A tractor cut across the upper beachface creating a trough in front of the heavily oiled section (see Fig. 4-50). Water under high pressure was then applied to the oiled cobbles. The oily runoff drained into the trough and was later collected.

Station F-94 at Primel-Trégastel is a sheltered rocky environment which acted as a perfect sink for the oil. Even after an extensive cleanup of the area, it was still heavily oiled on April 27.

Along the cliffed rocky coast between F-92 and F-91, mousse stringers were still seen floating on the water surface on April 27, more than 5 weeks after the beginning of the spill. Wave reflection kept most of the oil a short distance offshore (Plate 4-28). However, some small cobble coves became heavily oiled. Oil is not expected to remain in this area because of the highwave energy conditions.

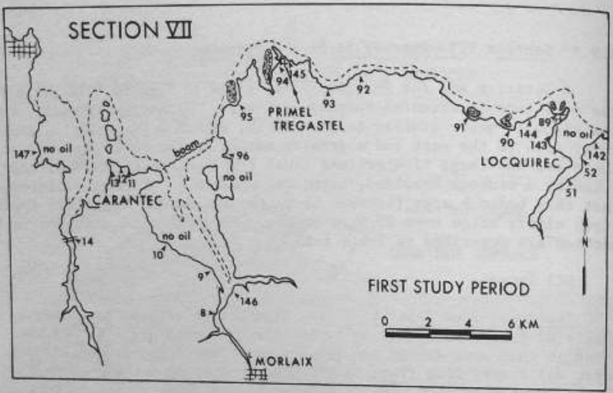


Figure 4-48. Location of stations in Section VII, Roscoff to Pointe de Plestin (F-142). Oil distribution during the first study session, March 19 to April 2, is indicated by the dark-stippled pattern.

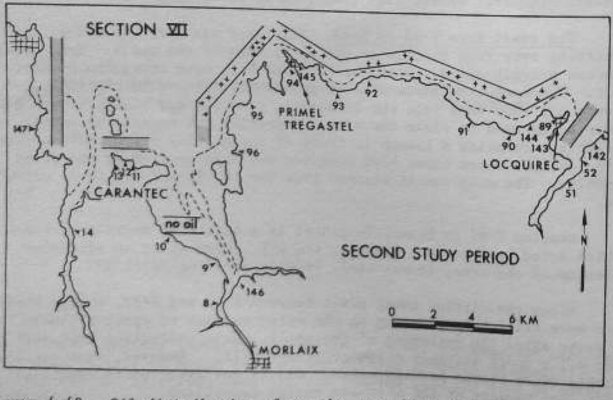


Figure 4-49. Oil distribution along the coastline of Section VII during the second study session, April 20-28. Heavy and light oil coverage are indicated by the plus and light-dot patterns, respectively.

Table 4-13. Field observations of oil distribution at stations of Section VII, Roscoff to Pte. de Plestin.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-147	27 Apr	Port de Pem Poul A seawalled harbor; coarse-sand tidal flat.	Light oil swashes.
F-14	24 Mar-	Pont de la Corde	-no oil.
	27 Apr-	Tidal flat/estuary with small channel; station at bridge over river.	-no oil.
F-13	24 Mar-	Carantec - West	-no oil.
	27 Apr-	A harbor with a sandy beach and large tidal flat.	-light oil swashes.
F-12	24 Mar	Carantec - North Near the mouth of a large estuary and tidal flat.	No oil.
F-11	24 Mar-	Carantec - East	-no oil.
	27 Apr-	Granule beach.	-very light oil on rocks; sand was removed to protect it from being oiled - it will be pushed back later; some light discontinuous burial.
F-10	24 Mar-	(near) Ty Nod	-no oil.
	27 Apr-	Gravel beach.	-no oil.
F-9	24 Mar-	East toward Dourduff	-no oil.
	27 Apr-	Tidal flat/estuary.	-no oil; possible light sheen in the water.
F-8	24 Mar	(near) Morlaix (2 km downriver) Small tidal flat with channel.	No oil
F-146	27 Apr	Dourduff en Mer Wide tidal flat area.	Clean except for an occasional mousse glob on the upper portion of the tidal flat (3 mousse globs/m^2); algae very productive.
F-96	2 Apr-	Terrenez	-no oil; boom deployed offshore.
	27 Apr-	Small harbor with cobble beaches on both sides.	-light oiling of cobble beaches.
F-95	2 Apr-	le Diben	-heavily oiled.
	27 Apr-	Cobble beach gently sloping onto a very rocky low-tide terrace.	-beach and rocks on low-tide terrace heavily oiled; extensive clean-up operation - tractors pushing oiled cobbles into lower swash zone to be cleaned by the waves; high pressure water also being used.
F-94	2 Apr-	Primel Trégastel - West	-very heavily oiled; extensive clean-up.
	27 Apr-	Sheltered harbor; cobble and boulder beach.	-moderately to heavily oiled; rocks are extensively coated with oil.
F-145	27 Apr	Primel Trégastel - East Gravel beach with a large sand tidal flat fronting it; backed by a seawall; upper beach portion consists of cobbles and boulders.	Upper beach is moderately to heavily oiled.

Table 4-13 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-93	2 Apr- 27 Apr-	St. Jean de Doigt Cobble and gravel beach.	-light oil on rocks. -rocks and gravel all heavily oiled; oil has sunk into the gravel beach; signs of previous clean-up effort.
F-92	2 Apr- 27 Apr-	West of St. Jean de Doigt Small rocky indentation of the coast.	-no oil on shore; mousse streaks offshore. -some mousse still in the water and now the rocks have a light coating of oil.
F-91	2 Apr- 27 Apr-	Poul Rodou Pocket beach surrounded by rocky headlands.	-no oil. -moderate to heavy oil on the rocks along the shoreline; light oil swashes on the beachface.
F-90	2 Apr- 27 Apr-	le Moulin de la Rive Cobble and gravel beach.	-moderately oiled rocks; clean low-tide terrace. -rocky area heavily oiled; low-tide terrace moderately oiled; active clean-up operation - a tractor is pushing oiled cobbles onto the lower beachface; also use of a high pressure hose.
F-144	27 Apr	les Sables Blancs Small sandy beach backed by dunes; algal covered rocks on low-tide terrace; rocky headlands on both sides.	Headlands moderately oiled; light oil swashes on beach; location of an oil storage pit.
F-89	2 Apr- 27 Apr-	Locquirec Rocky and sandy beach with a similar low-tide terrace.	-moderately oiled rocky area. -rocks are moderately to heavily oiled; even the rocks on the low-tide terrace are oiled; a very small clean-up attempt is in effect - mainly steam cleaning.
F-143	27 Apr	Locquirec Port Small jetty protecting a little harbor.	Both sides of jetty clean and no oil in the water; boom in place at front of the port; this area is very biologically productive.
F-51	28 Mar- 27 Apr-	Toul an Héry Upper part of tidal flat in harbor.	-no oil. -light coating of mousse globs along the shoreline; some very light oiling of the seaweed.
F-52	28 Mar- 27 Apr-	(near) Kerdrehoret - West Beach and tidal flat in harbor.	-no oil. -very light oiling here - one small oil glob for each 2 square meters; otherwise, completely clean.
F-142	27 Apr	(near) Kerdrehoret - North Small fine-sand pocket beach.	Some oil droplets on the surface of the rocks; beach is entirely clean; no burial.

Figure 4-50. Oil clean-up at the cobble beach at station F-95 on April 27. A tractor created the runoff trench at the foot of the beach. High pressure water helped remove the deeply penetrated oil from the cobbles. The method is sound from a coastal geomorphic standpoint since beach sediment is not removed. Reworking by waves will re-establish the normal beach profile.

Closer to Locquirec, most of the rocks were still moderately oiled on April 27. At F-90, a tractor was pushing oiled gravel into the swash zone, and a small steam cleanup operation was in effect at F-89.

The coast between F-143 and F-142. This large embayment reacted similarly to those at the western side of Section VII. No oil was initially deposited along the shoreline, since the Locquirec peninsula acted as a barrier. However, during the survey on April 27, light swash lines of small mousse balls (less than 1.0 cm in diameter) were found throughout the area. These mousse balls apparently drifted in as a result of shift in wind direction.

Summary

Two points of interest are illustrated in Section VII:

(1) It is possible to use tractors and high pressure water to clean heavily oiled coarse gravel beaches without removing the gravel.

(2) Thick mousse stringers remained in the nearshore water more than 5 weeks after the beginning of the oil spill. Therefore, previously unoiled areas were still subject to potential pollution, depending upon the vagaries of the winds and currents.

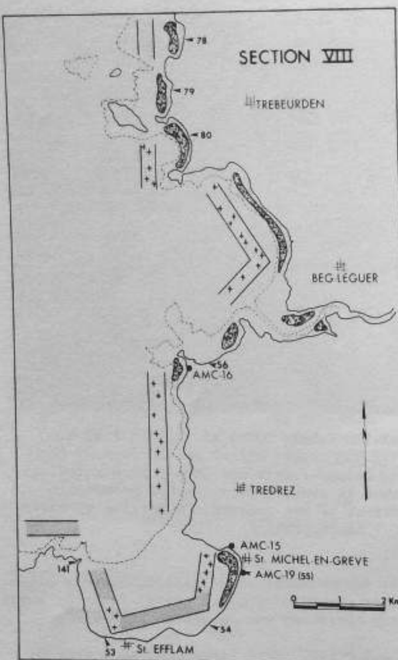


Figure 4-51. Location of survey stations in Section VIII (St. Efflam to Kerhellen). This section included the large sand flat at St. Michel-en-Grève. Oil distribution for study period one is indicated by the dark-stippled pattern. Heavy and light oil coverage during the second study period are indicated by the plus and light-dot patterns, respectively.

4.9.8 Section VIII--St. Efflam to Kerhellen

This section includes the broad sandflat called the Grève de St. Michel, as well as a cliffed, north-south trending bedrock shoreline (Fig. 4-51). The sandflat of St. Michel, which extends for over 2 km from the high tide line to the low tide line, was the scene of a massive oil-caused kill of most of the shelled infaunal organisms. For this reason, this area will be discussed in detail. The extent of oiling along the bedrock system was generally heavy, increasing toward the north. The summary of our field observations for this section is presented in Table 4-14.

Table 4-14. Field observations of oil distribution at stations of Section VIII, St. Efflam to Kerhellen.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-141	27 Apr	Pointe de Plestin Exposed pocket beach consisting of medium- to coarse-grained shell material.	No oil except for very light oil splattering along the high tide swash lines.
F-53	28 Mar- 27 Apr-	les Carrières Large tidal flat embayment.	-no oil -some heavily oiled rocks; no oil at the lower portion of the tidal flat.
F-54	28 Mar- 2 Apr- 27 Apr-	St. Michel-en-Grève (South) Large tidal flat embayment.	-oiled swash lines and some small mousse pools. -millions of dead organisms. -light sheen on upper tidal flat; no oil on the lower portion.
AMC-19 (F-55)	28 Mar (F)- 2 Apr (F)- 25 Apr (AMC)-	St. Michel-en-Grève Very large sand flat/embayment.	-heavily oiled along upper portion of beach; large clean-up operation with much manpower and many tractors; oil contaminated interstitial water. -millions of dead organisms. -light swashes on beach; oil buried (30 cm) in infilled collection troughs; interstitial water still oil contaminated.
AMC-15	28 Mar- 25 Apr-	St. Michel-en-Grève (NE corner) Mixed sand and gravel beach on edge of very fine-sand tidal flat.	-80 to 100% oil coverage of the beachface and near edge of tidal flat. -still heavily oiled beachface and rocky edge of tidal flat; signs of an extensive clean-up operation; interstitial water oil saturated.
AMC-16	28 Mar- 24 Apr-	Pointe de Sehar Large pebble beach between two bedrock areas.	-very heavily oiled; 30 cm penetration of oil into the gravel along the upper beachface. -still oil soaked; at least 15 cm penetration over entire beachface; presence of a bulldozer pushing oiled gravel into furrows to be re-washed by incoming tide and waves.
F-56	28 Mar	Plage de Notigou Sandy pocket beach with out-cropping rocks.	Heavily oiled beach and rocks.
F-80	31 Mar- 25 Apr-	Plage de Tresmeur Cobble beach leading onto a sandy low-tide terrace.	-heavily oiled. -cobble moderately oiled; low-tide terrace very clean; tractor pushing cobbles seaward so as to allow natural cleansing; high pressure hoses also in use to clean the rocks.
F-79	31 Mar- 25 Apr-	Plage de Porz Termen Medium- to coarse-grained beach within a harbor.	-heavily oiled. -beachface is clean but the rip-rap walls behind the beach are heavily oiled.
F-78	31 Mar- 25 Apr-	Kerhellen Coarse sandy beach with rocks on both sides.	-heavily oiled. -rocks on both sides moderately oiled; light oil along the last high tide swash line; also much burial along the upper beachface.

Oil Impact

St. Michel-en-Grève. Observations at St. Michel-en-Grève present one of the most massive kills of infauna by oil ever recorded. The initial site visit on March 28 showed extensive oil coverage within the southeast pocket of this tidal flat/fine-sand beach. A large cleanup operation was underway (see Plates 4-4, 4-5, 6-8, 6-9, 6-24), but no biological damage was evident.

By the time of our return visit on April 2, the entire 2 km of sand flat was littered with millions of shells, including empty shells of heart urchins, tissue-laden shells of razor clams, and many small bivalves (see Plates 4-6, 4-7, 5-10, 5-11, 5-12, 5-13).

Approximately 1 km from the beach, samples were taken for infaunal analysis. Living annelids and polychaetes were found. Shelled infauna were not present. The ground water was contaminated with oil.

Three estimates of numbers of dead organisms were made:

(1) A swash line of dead heart urchins (Echinocardium sp.) 300 m long and 25 m wide was counted, based on the number of dead organisms occurring within a one-meter wide swath measured perpendicular to the swash line. The total arrived at was 120,000 dead urchins within that one swash line.

(2) A swash line (250 m long and 6 m wide), made up predominantly of dead razor clams, was also measured using the same method as in 1. According to our estimate, there were 45,000 dead razor clams within that single swash line.

(3) At evening low tide (7:00 p.m.) on April 2, the entire intertidal area was littered with shells of dead organisms (Plate 4-4). As the tide fell, a cover of approximately 3 to 5 dead organisms/m^2 was left behind. Heart urchins were by far the dominant species. At that time, the intertidal zone was measured to be 570 m wide. Assuming that each square meter contained four dead urchins (based on several counts), a 500 m long section of the beach would have contained 1,140,000 dead urchins. Therefore, several million dead urchins were present on the surface of the intertidal zone at that time, in addition to hundreds of thousands of dead clams and worms.

Claude J. M. Chassé of the University of Brest completed an extensive Ph.D. study of this flat (and other areas) in 1972 (Chassé, 1972). Apparently, follow-up studies will be carried out under his direction.

We revisited the St. Michel-en-Grève sandflat on April 25. All dead organisms had been collected and removed from the surface of the flat. Approximately 1 km from shore, oiled rubble (mostly coarse gravel)

had been placed on the flat apparently to be cleaned by wave action (similar to that illustrated in Plate 6-30). Interstitial water in the area was still contaminated with oil.

Because we wanted to monitor the effects of the cleanup operation, particularly the digging of numerous trenches in the intertidal zone, we established a new profile site (AMC-19) at St. Michel-en-Grève. The topographic profile of the beach is shown in Figure 4-52. Sediment data are presented in Table 4-15A. At the time of our survey, light oil swash lines were found on the surface of the flat. However, the oiled remains of three cleanup trenches were located (Fig. 4-52, see also Plate 6-23). A maximum of 35 cm depth of oiled sediment was measured. This profile site will be reoccupied to determine the persistence of the remaining oil. As at other sites, this could prove to be a long-term source of interstitial water contamination.

Station AMC-15 is a mixed sand and gravel beach located at the northeast edge of the St. Michel sandflat. In some parts of the beach, a thin veneer of fine sediment was deposited over compact coarser material. The beach profile and oil coverage for the station on March 28 are presented in Figure 4-53.

During the site survey on March 28, the beach at AMC-15 was heavily contaminated (see Plate 4-13). We estimate that 83 metric tons of oil were in the area (Table 4-15B). Oil extended approximately 50 m onto the sandflat. During our second survey, April 25, the beachface was still blackened in appearance, although the thick accumulations of oil were gone. The remaining quantity of oil was estimated at 4 metric tons. There were signs of a cleanup operation, so natural processes were not completely responsible for the oil removal. No oil burial was in evidence; however, the interstitial water was noticeably contaminated.

St. Michel-en-Grève to Pte. de Sehar. The coastline directly north of the St. Michel-en-Grève sand flat consists of steeply dipping, 70 m cliffs, half of which border the sandflat. Because of its north-south orientation, it became heavily oiled during the first two weeks of the spill. It was still oiled on April 28.

Station AMC-6, which is located at the northmost end of the bedrock cliffs, consists of a long, steeply dipping pebble beach (mean grain size = -4.690; Table 4-15). The topographic profile and areas of oil coverage for this site are presented in Figure 4-54. On March 28, the area was heavily oiled (see Plate 4-14). Digging into the beach, we found that taffy-like mousse had penetrated over 20 cm into the sediment (Plate 4-15). The estimated quantity of oil in the area was placed at 81 metric tons, much of which was incorporated into the beach sediment.

Returning to the site on April 24, we found the area to be little different from before. Oil was still on the beach surface and had

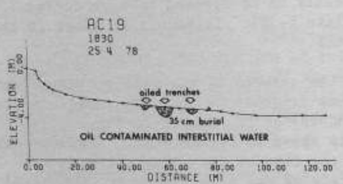


Figure 4-52. Topographic beach profile of station AMC-19 on April 25. Oiled trenches remaining from the clean-up operation are indicated.

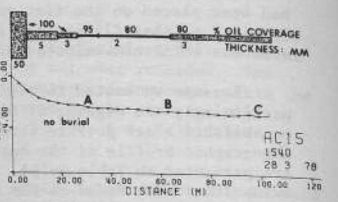


Figure 4-53. Topographic profile and oil coverage of the beach at site AMC-15 on March 28. Oil was restricted to the beach face and uppermost portion of the sand flat.

penetrated 15 to 20 cm into the sediment over the entire beachface. Our calculated tonnage of oil present was 66 metric tons, indicating little change from the previous visit.

During our earlier studies of the Metula spill site in Patagonia, we had seen similarly oiled gravel completely cemented as the mousse dried and turned to asphalt. In an apparent effort to avoid a similar situation at AMC-16, the cleanup crews used a bulldozer to push the oiled gravel seaward into furrows where the waves (at high tide) could rework the sediment, thus removing some of the oil (Fig. 4-55A). This is a valid method since sediment is not removed from the beach and it provides an artificial mechanism of mixing the oiled gravel before it becomes cemented by asphalt. In the future, wave action will probably restore the normal beach profile without marked erosion. The rapidity of beach cleaning will depend upon the amount of wave action.

The coast from Pte. de Sehar to Kerhellen. This section of coast consists of small beaches, steep cliffs, and a large ria. Some of the oil that passed by Roscoff was deposited in this area. Most of this coast was observed to be heavily oiled at the end of March. During the site surveys and aerial reconnaissance of late April, most of the area was still moderately oiled. The tidal flat leading toward Beg-Leguer was heavily oiled. Cleanup activity similar to that at AMC-16 was in progress at F-80. Oil-soaked cobbles along the seawall were being pushed onto the low-tide terrace to be cleaned by natural wave action (Fig. 4-55B).

Table 4-15A. Sediment data for AMC stations in Section VIII.

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-15A	3.136	VFS	-0.057	0.461 (WS)
AMC-15B	0.926	CS	-0.633	2.819 (VPS)
AMC-15C	3.277	VFS	-0.052	0.363 (WS)
AMC-16A	-4.693	P	0.149	0.330 (VWS)
AMC-19A	3.220	VFS	-0.217	0.393 (WS)
AMC-19B	3.319	VFS	-0.124	0.353 (WS)
AMC-19C	3.310	VFS	-0.141	0.336 (VWS)

[1]Size Class

VFS = very fine-sand
CS = coarse-sand
P = pebbles

[2]Sorting

VWS = very well sorted
WS = well sorted
VPS = very poorly sorted

Table 4-15B. Estimates of oil tonnage for AMC stations in Section VIII.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-15	28 Mar	83.3	25 Apr	3.9	95.30
AMC-16	28 Mar	81.2	24 Apr	66.3	184.00
AMC-19	NO DATA				

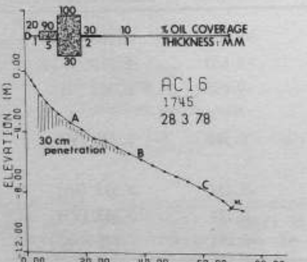


Figure 4-54. Topographic beach profile and oil coverage for station AMC-16 on March 28. Our return site survey on April 24 indicated that oil had penetrated 15 to 20 cm across the entire beach face.

Summary

The most striking observation in this area was the tremendous biological damage at the sand flat at St. Michel-en-Grève, even though it was located 87 km from the wreck. Also, the technique used to clean the heavily oiled gravel beaches may have applicability in New England and Alaska where similar beaches are prevalent, should oil spills occur in those areas.

4.9.9 Section IX--Ile Grande area

This section is one of the more important ones, because it includes a heavily impacted marsh area (Figs. 4-56 and 4-57). The general orientation of this shoreline is northeast-southwest. A large sandflat with scattered bedrock outcrops makes up most of the area. Except for the outer beaches of Ile Grande, the area is exposed to very little wave action. On a large scale map, it can be seen that this entire area protrudes out from the general shoreline trend (Fig. 4-1) making it a perfect interception point for the oil that bypassed Roscoff. Descriptions of the study sites are given in Table 4-16.

Oil Impact

All areas, except station F-76, were observed to be heavily oiled during site visits at the end of March and April. Station F-76 is an exposed, high-energy beach composed of large granitic boulders that was only lightly oiled. Sheltered areas at F-88, F-77, and F-75 had been cleaned or were in the process of being cleaned, but still appeared heavily oiled on April 25. Heavy machinery often mixed the oil deep into the beach or tidal flat sediments, which made it impossible to remove all the oil.

Figure 4-55. (A) Heavily oiled cobbles of station AMC-16 were pushed into furrows to aid cleaning by wave action. (B) At station F-80, a similar method of clean-up was in operation.

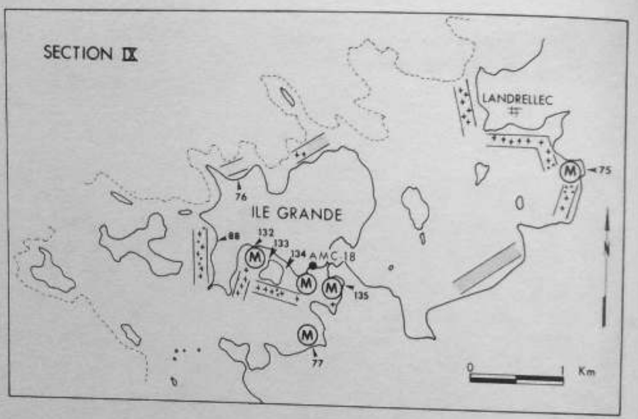


Figure 4-56. Locations of observation stations in Section IX. Oil coverage for the second study period is indicated as follows: heavy oiling--pluses, light oiling--dot pattern, and oiled marshes--circled M's.

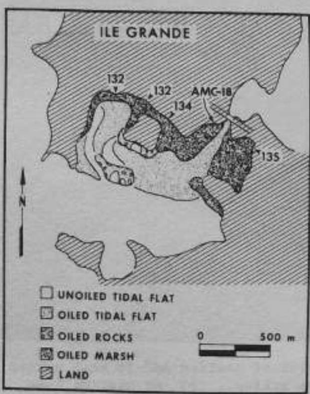


Figure 4-57. The Ile Grande marsh area observation stations and oil distribution on the tidal flat and marsh.

Table 4-16. Field observations of oil distribution at stations of Section IX, the Ile Grande area.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-77	31 Mar-	Runigou	-heavily oiled.
	25 Apr-	A sand flat with a rip-rap wall along the sides of the flat. A small marsh is also in the area.	-sand flat all clean; rip-rap wall still heavily oiled; marsh remains moderately oiled.
F-135	25 Apr-	Allée Couverte South side of Ile Grande Marsh; vegetation mainly Juncus marsh grass.	-very heavily oiled, cleanup operation in progress; 5 cm of oil on much of the marsh; soldiers using squeegees to push the oil into the channels where it is being pumped out.
AMC-18	29 Mar-	Ile Grande Marsh, and west side of D21 bridge to Ile Grande Large marsh with a wide, muddy sand channel.	-very heavily oiled; oil pools to 27 cm deep; average coverage about 3 cm; thousands of polychaetes worms crawling over the surface of the oil to escape.
	2 Apr-		-oil in same condition; polychaetes all dead and often found in small water pools on the surface of the oil.
	24 Apr-		-visit at hightide; only a light sheen visible on water surface.
	25 Apr-		-area has been manually cleaned; large oil pools drained; marsh still very black but some new green grass shoots appearing.
F-134	25 Apr-	West Road to Rulosquet Part of Ile Grande Marsh area.	-area oiled; extensive clean-up operation underway: light sprinkler system rinsing the marsh as well as high-pressure hosing.
F-133	25 Apr-	East Road to Rulosquet Part of Ile Grande Marsh area.	-still completely oiled; many trenches dug to drain oil; blackened; large clean-up underway.
F-132	25 Apr-	Dourlin Western side of Ile Grande Marsh--a narrow fringing marsh beside a sand flat.	-section 20 m wide remains thinly oiled after clean-up; numerous tire tracks, ditches, trenches on the sand flat as a result of clean-up.
F-88	2 Apr-	Ile Grande Beach (East Facing)	-heavily oiled.
	25 Apr-	Sheltered sandy pocket beach; wave energy usually low due to an island directly offshore.	-heavily oiled shoreline and tidal flat.
F-76	29 Mar-	Northwest Ile Grande Boulder beach.	-lightly oiled boulder beach.
	25 Apr-		-light oil coverage on boulders.
F-75	29 Mar-	(Near) Kerenoc	-small marsh and rocks heavily oiled.
	25 Apr-	Small marsh in northeast corner of large sand flat, with some rocks.	-very heavily oiled marsh grasses; some rocks with algae are completely oil covered; a large trench, dug to collect oil, causes serious oiling of the surface of the tidal flat.

The marsh at Ile Grande presents the most striking effects of oil impact in the entire spill site, especially considering that the oil was transported at least 86 km (53 miles) before it came ashore. During our first survey on March 29, we found oil on the marsh grasses as well as on the tidal flat surface. Plate 4-1 shows the oil coverage at that time. Both the marsh and tidal flat were heavily oiled (Fig. 4-57). Several ground-level photographs are presented in Plates 4-2, 4-3, 5-7, 5-8 and 5-9.

This area provides an excellent opportunity for U.S. scientists to study the effects of oil on a large marsh, tidal flat ecosystem, inasmuch as the types of marsh grasses and infaunal assemblages are similar to those in the eastern U.S. The marsh grasses are distinctly segregated by topography. Figure 4-58 (station AMC-15) gives a sketch of the area, as well as the marsh plant zonation. Briefly, from the high tide line seaward, the grasses consist of Juncus sp., Spartina patens and a succulent common to northern Europe called Sesuvium sp.

At the time of our first site visit on March 29, 3 to 5 cm of oil covered the entire marsh area. Oil thickness and surface area coverage as measured along our profile line are shown in Figure 4-59. On the tidal flat surface, oil was approximately 1 cm thick. Within many tidal pools (approx. 3 m x 1 m) on the surface of the flat, oil reached 15 cm in thickness. In our calculations of the approximate quantity of oil within the marsh system, we assumed an average value of 3 cm of oil over most of the oiled marsh and an average of 1 cm on the flat surface. An average thickness of 5 cm was measured for the marsh at F-135. By measuring the area of each marsh as marked in Figure 4-57, we estimate that 7400 metric tons of oil were present on March 29 (Table 4-17).

At the time of our first site inspection on March 29, thousands of moribund polychaetes were found on the surface of the marsh. Many were observed wriggling on the surface of the oil pools. By the time of our return visit on April 2, the marsh was dead. Thousands of dead polychaetes littered the surface of the marsh, and collected in small salt-water pools within large (2 m x 1 m) oil pools. Crabs were found dead. Grasses were completely blackened. Four oil-covered, dead cormorants were also found.

Our third site visit, on April 25, proved to be most interesting. The French military had begun an enormous cleanup operation within the area and about 80% of the marsh on the north side had been cleaned in some manner. In addition, 90% of the tidal flat was free of oil. Cleanup activities as observed at sites F-133, F-134 and F-135 (AMC-18 and F-132 had been cleaned already), consisted of high-pressure hosing (Figure 4-60A), low-pressure sprinkling, trenching of the thick oil pools, placement of oil into buckets, and use of tank trucks to remove oil from trenches or newly created pits. Over 200 men were working when we were there. The operation was successful in ridding the marsh and tidal flat of an enormous quantity of oil. Measuring along our profile

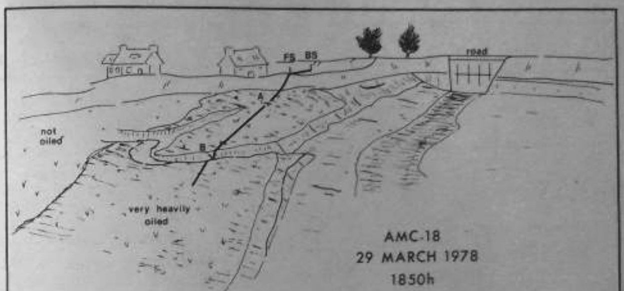


Figure 4-58. Topographic profile and oil coverage for station AMC-18 (Ile Grande marsh) on March 29. Oil distribution along the profile is indicated in Figure 4-59.

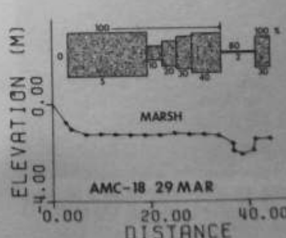


Figure 4-59. Oil coverage along profile AMC-18 (Ile Grande marsh) on March 29. The thickness of the depicted oil coverage line is roughly proportional to actual thicknesses.

Table 4-17A. Grain size data for station AMC-18 in Section IX (Ile Grande marsh).

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-18A	4.613	CS	-0.295	1.863 (VPS)
AMC-18B	2.100	FS	-0.134	0.934 (MS)

[1]Size Class

CS = coarse silt
FS = fine sand

[2]Sorting

VPS = very poorly sorted
MS = moderately sorted

Table 4-17B. Calculations of oil quantity at AMC-18 during first (March 19-April 2) and second (April 20-28) study periods.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-18	29 Mar	7400	25 Apr	2761.8	63.00

(station AMC-18), we found an average oil layer of 4 mm mostly coating the bottom sediments and grasses. We calculated the oil tonnage at this time on the following basis:

(1) 20% of the original oiling (3 cm) remained on the north side, with 80% being lightly oiled (4 mm);

(2) 5 cm oiling at F-135; and

(3) 10% of the original 1 cm oiling on the tidal flat.

On the basis of these assumptions, we estimate that 2762 metric tons of oil remained in the Ile Grande marsh area on April 25. This is a 63% reduction from our estimate for March 29 (before cleanup).

Cleanup techniques could have been improved had personnel and machinery been directed to maintain a single road or work path. The unrestricted movement of men and machinery on the surface of the marsh and tidal flat caused extra destruction of vegetation and churned oil deep into the underlying sediment (Figure 4-60B).

Figure 4-60. (A) High-pressured hosing of the Ile Grande marsh on April 25 (station F-134). (B) The use of heavy machinery on the tidal flat at Ile Grande tended to churn up much of the area and mix oil deep into the sediment (station F-133, April 25).

One of the best opportunities for study in this area would be a time-series investigation of biological recovery. For example, although almost all of the marsh grasses were still blackened by oil on April 25, newly sprouted green marsh grass was already visible. Live fish and crabs were also seen in tidal pools within the main channel.

Summary

The Ile Grande marsh area has illustrated the enormous impact a massive oil spill can have on a thriving marsh/tidal flat ecosystem. This marsh in particular offers an excellent opportunity to monitor marsh recovery after a major spill. It would also be of interest to compare the recovery of this marsh with that of the marsh at Punta Espora, Chile, which was impacted by a heavy dose of Metula oil in August 1973. That marsh, which was not cleaned, has been very slow to recover (Hayes and Gundlach, 1975).

4.9.10 Section X--Landrellec to Trestel

Section X is the northernmost extension of the granitic plateau of which Ile Grande is a part (Fig. 4-61). Much of the area near the coast is less than 20 m above sea level except by Ploumanac'h, where cliffs over 40 m are present. Major depositional embayments with large sand flats are located at Ploumanac'h and Perros-Guirec, where the mean tidal range has increased to 8 m. This is one of the more popular tourist areas of this section of Brittany. Individual study site descriptions are given in Table 4-18.

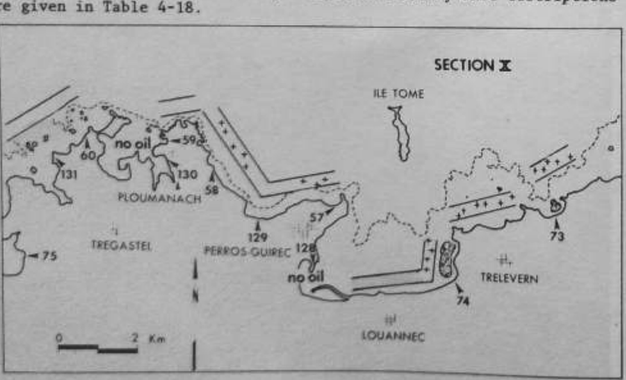


Figure 4-61. Locations of observation stations in Section X, Landrellec to Trestel. Oil distribution for the first study session is indicated by the dark-stippled pattern. For the second study period, heavy and light oil coverage are indicated by the plus and light-dot patterns, respectively.

Table 4-18. Field observations of oil distribution at stations of Section X, Landrellec to Trestel.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-131	25 Apr-	la Grève Blanche Sandy beach with a large tidal flat and outcropping rocks.	-the beach is very clean with a clean tidal flat; the rocks are somewhat oiled, and are presently being cleaned by a power hose from a water tank-truck.
F-60	28 Mar-	Coz Porz Coarse-sand beach with large rocks offshore.	-lightly oiled; sand removed from beach as protection measure.
	25 Apr-		-a few isolated mousse balls on the beach; a light oiling on the offshore rocks.
F-130	25 Apr-	Ploumanac'h - South Harbor with a sandy beach.	-clean except for a few oil globs; the rocks have been artificially cleaned.
F-59	28 Mar-	Ploumanac'h - North Protected small pocket beach; coarse-sand and gravel.	-moderately oiled.
	25 Apr-		-a clean beach; no buried oil layers, but the groundwater is oil saturated.
F-58	28 Mar-	East of Ploumanac'h Rocky coast with some small gravel and cobble pocket beaches.	-rocks clean; an oil sheen is on the water.
	25 Apr-		-the pocket beaches are heavily oiled; exposed headlands are very lightly oiled; clean-up in progress.
F-129	25 Apr-	Plage de Trestraou Large fine-sand pocket beach located between two rocky headlands which project almost due north.	-some light oil swashes on the beach; also some oiled cobbles being buried by the fine sand; a tractor is digging up the cobbles and pushing them seaward so that the waves can clean them.
F-57	28 Mar-	Plage de Trestraou Sandy pocket beach.	-very clean except for a light sheen in the water.
F-128	25 Apr-	Perros-Guirec Jetty and harbor.	-jetty lightly oiled on the ocean side; no oil in the interior of the harbor; boom across harbor.
F-74	29 Mar-	Nanthouar Large gravel beach.	-rocky area heavily oiled.
	24 Apr-		-lightly oiled swash line on the beach; rocks to the west are moderately to heavily oiled.
F-73	24 Mar-	Plage de Trestel Medium-sand tidal flat and beach.	-beach is clean; a new seawall is covered with plastic so as to prevent its oiling.
	24 Apr-		-seawall still covered with plastic, so far unoiled; a few light oil swash lines on the beach.

Oil Impact

Initial oil impact for most of the area was very light to moderate (Table 4-18). Only Stations F-74 and F-73 received major accumulations. Most of the oil still in the water drifted by without hitting the coast. Station F-60, which would have been expected to be oiled, was apparently protected by offshore rocks (see Figure 4-61). All areas on the east side of the Ploumanac'h peninsula were on the sheltered side during the westerly wind and were not initially oiled.

However, during our second study session, April 23, the coast was much more heavily oiled. Apparently, the wind shift caused the oiling of the previously clean areas on the lee-side of the headlands. Rocky areas were particularly hard hit, especially at stations F-57 and F-58. The area from F-74 to F-73 also was more heavily oiled than during the first study session. As was common at the other sections, the oil spill changed from having large oil pools at particular areas to being spread in varying quantities over the entire coastline. In many localities, the beach had become cleaner, but the rocks alongside the beach were more heavily oiled. A definite shift of oil from the beaches to within sheltered rocky areas had taken place.

Summary

Section X illustrates a standard pattern of oil dispersal for the oil spill area. Sites previously sheltered from oil deposition (e.g. F-57 and F-58) during the first two weeks of the spill, became heavily oiled after the wind shift. Beaches were cleaned much more rapidly than sheltered rocky areas. In fact, the rocks probably act as a sink for some of the oil washing off the beaches.

4.9.11 Section XI--Port Blanc to Sillon de Talbert

Section XI represents the farthest easterly extent of oil coverage that we observed (Fig. 4-62). The base of Sillon de Talbert is 130 km from the wreck site (by the most direct ocean route). On March 30, we flew the section of coast from Mont St. Michel Abbey to Sillon de Talbert and found no oil along the coast. Only a few small mousse patches were seen in these waters. Table 4-19 contains descriptions of the individual study sites.

The coastline in Section XI consists of two large granitic headlands separated by a large tidal flat/estuarine system. The tidal range reaches between 8.5 and 9.0 m. Many beaches of the area are naturally crenulate in shape (F-66, F-68 and AMC-17). The role of crenulate beaches as a localized control of oil deposition will be discussed in the following section.

Table 4-19. Field observations of oil distribution at stations of Section XI, Port Blanc to Sillon de Talbert.

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-72	29 Mar- 24 Apr-	Les Dunes near Port Blanc Sand and gravel beach with a large tidal flat and dunes.	-heavily oiled gravel and rip-rap near dune area. -minor oiling along the high tide swash line; the tidal flat is very clean.
F-71	29 Mar-	Crech Arel Sandy beach with low-tide terrace.	-clean beach but some oiled rocks.
F-70	29 Mar- 24 Apr-	(Near) Pellinic Marsh.	-oiled marsh covered by an average 3 cm of oil. -still very heavily oiled; no clean-up.
F-69	29 Mar- 24 Apr-	Bugelos - Coz Castel Tidal flat surrounded by large rocks.	-oiled rocks surrounding large tidal flat. -rocks still appear heavily oiled; no oil on tidal flat itself; marsh grasses appear oiled; clean-up operation has left area completely dug-up.
F-127	24 Apr	Anse de Gournel Large sandy tidal flat.	Sand flat is very bioproductive; thousands of worm burrows and many cockles; beach and tidal flat are clean except for a minor oiled sea-weed swash line along the last high tide swash; rocky areas on both sides of this sand area are heavily oiled.
F-68	29 Mar- 24 Apr-	(near) Kergonet Sandy beach with large tidal flat.	-tidal flat and rocks both oiled. -very heavily oiled along the upper portions of the tidal flat as well as the beachface; tidal flat itself is all soaked with oil; trenches dug to trap and pump out the oil remain heavily oiled.
F-67	29 Mar- 24 Apr-	Porz Scaff Small pocket beach with a seawall behing it.	-oiled gravel and rocks. -all the cobble on the beach are heavily oiled as is most of the lower beachface.
F-66	29 Mar- 24 Apr-	Castel Meur Gravel and cobble beach with a large tidal flat; many cobbles outcrop on the tidal flat.	-heavily oiled gravel beach; large clean-up operation underway. -very heavily oiled here; mousse is 1-2 cm thick on much of the beach; some of the limpets have survived but many dead cockles and crabs are seen floating in oil pools; straw used to absorb some of the oil is still on the beach and tidal flat.
F-65	29 Mar- 24 Apr-	Porz Bugale Small, mixed sand and cobble beach.	-no oil. -light oiled swash line along the last high tide line.
F-64	29 Mar	Tréguier Estuarine tidal flat with a major channel flowing north.	No oil.

Table 4-19 (continued)

Station Number	Date(s) Visited	Location and Type of Environment	Description of Oil Impact
F-126	24 Apr	Luzuret Broad rocky tidal flat.	Beach area clean; rocks very lightly oiled.
F-63	29 Mar- 24 Apr-	Plage de Beni Sand and cobble beach.	-no oil. -lightly oiled swash lines.
F-62	29 Mar	Kermagen Boulder and cobble beach.	A little oil on the boulders.
AMC-17	29 Mar- 24 Apr-	Port la Chaine Coarse-sand crenulate-shaped beach between rocky headlands.	-very thick oil accummulations on beach; oil contaminated interstitial water. -light oil staining of beach sediments; some oil buried on beachface (15 cm) and on low-tide terrace; interstitial water still contaminated.
F-125	24 Apr	le Quebo Mixed sand and gravel beach.	Some minor oil blotches on the rocks; otherwise completely clean.
F-61	29 Mar- 24 Apr-	Sillon de Talbert A flying gravel spit.	-lightly oiled rocks; clean beach. -rocks lightly oiled; this is the furthest eastern extent of the oiling.

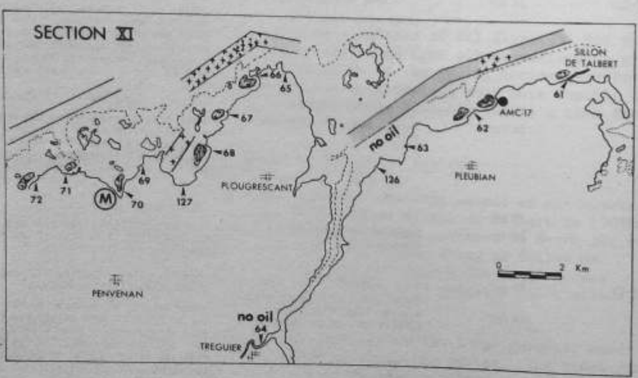


Figure 4-62. Locations of observation stations in Section XI, Port Blanc to Sillon de Talbert. Oil at the base of Sillon de Talbert represents the eastern-most extent of oil coverage observed. It is 130 km (77 miles) from the wreck site. Oil distribution for the first study session is indicated by the dark-stippled pattern. For the second study period, heavy and light oil coverage are indicated by plus and light-dot patterns, respectively.

Oil Impact

The coast from F-72 to F-66. Oil impact increased toward the north in the areas not shielded by the peninsula at Ploumanac'h (Section X). Initially, moderate to heavy oil accumulations occurred on most of these beaches. Particularly hard hit was the headland at Castel Meur (F-66) which is located at the end of the peninsula. The cobble beach and adjacent sand flat were very heavily oiled. A large cleanup operation was active during our site visit on March 29. Oil was being pushed into newly dug trenches on the low-tide terrace so it could be suctioned-up by honeywagons. Two large oil storage pits were dug nearby as collecting ponds. Upon our second visit on April 24, the area was still heavily oiled, although most of the thick oil accumulations were gone. The cobbles and boulders of the beach were still oil-blackened. The tidal flat was severely dug up. The trenches had infilled but remained severely oiled. An oil sheen was common throughout the area. Live limpets were observed on the rocks, but many cockles and crabs were found dead.

Speaking to a woman who lives by this beach, we learned that she depended on two things for her livelihood: summer tourists who come to the beach, and the collection of algae from along the swashline. Both sources of income were at least temporarily destroyed by the spill.

The coast from F-65 to Sillon de Talbert. This segment includes a large estuarine sandflat system plus the rocky coast up to the Sillon de Talbert gravel spit. To our knowledge, no oil entered the estuary during the first two weeks of the spill. During our second survey, April 24, a light oil swash was present on all these beaches.

Station AMC-17 had the heaviest deposition of oil within this section and represents the major accumulation farthest from the wreck site. It has a poorly sorted, mixed sand and gravel beachface leading onto a very coarse-sand low-tide terrace. Sedimentary characteristics are presented in Table 4-20A. The overall shape of the beach is crenulate in nature, which served as a trap for the wind-transported oil. Oil was thickly deposited (up to 12 cm) at the northern end of the beach on March 29, whereas the beach to the south was free of oil. Plate 4-31 shows the beach at this time. Oil coverage as measured along the topographic profile is presented in Figure 4-63. Penetration of oil into the beach was greatly inhibited by the compact substrate. The interstitial water of the low-tide terrace was noticeably contaminated. We estimate that 126 metric tons of oil were present at this time (Table 4-20B). The military began to clean up the beach as we finished our survey. The hard substrate made it relatively easy to shovel up the oil into buckets to be carted away by tractors.

On our second survey, on April 24, the major oil accumulation was gone, but the beach sediment and rocks appeared heavily oil-stained. In

Table 4-20A. Grain size data for station AMC-17 in Section XI.

Sample	Graphic Mean	Size Class[1]	Skewness	Standard Deviation[2]
AMC-17A	-0.174	VCS	-0.238	2.236 (VPS)
AMC-17B	1.461	CS	-0.266	0.713 (MS)
AMC-17C	-0.577	VCS	-0.498	2.000 (VPS)

[1]Size Class
VCS = very coarse sand
CS = coarse sand

[2]Sorting
VPS = very poorly sorted
MS = moderately sorted

Table 4-20B. Calculations of oil quantity at AMC-17 during first (March 19-April 2) and second (April 20-28) study periods.

Station Number	Date	Oil Present (metric tons)	Date	Oil Present (metric tons)	% Change
AMC-17	29 Mar	136.4	24 Apr	1.6	98.80

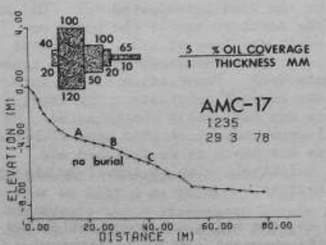


Figure 4-63. Topographic profile and oil coverage for AMC-17 on March 29.

addition, some oil was buried 15 cm by new sediment along the upper beachface. A large (100 m^2) mass of mousse also remained mixed into the low-tide terrace. The interstitial water was still contaminated, but healthy algae, snails, and limpets were found in abundance. We estimate that 1.6 metric tons of oil remained in the area (Table 4-20B). It was interesting that a large cobble beach directly to the south was significantly oiled on the second visit, whereas it had not been during the first. Apparently, some of the oil from AMC-17, or from other beaches, was redeposited in this area during the weeks between our first and second surveys.

Summary

Section XI encompasses the westernmost extent of oil pollution from the Amoco Cadiz (a distance of 130 km from the wreck). Station AMC-17 illustrates the importance of the trapping of oil along the northeast side of a crenulate bay during the first oiling and the eventual oiling of the southwest side as a result of a change in the wind direction. (According to C. J. M. Chassé, personal communication, the same thing happened on this coast during the pollution by the Torrey Canyon oil in 1967).

4.10 Preliminary Conclusions

When our second site visit ended on April 28, significant quantities of oil remained in the water and on the shoreline of the Amoco Cadiz oil spill site. It may take several years, or at least several months, for the remaining oil to be fully degraded. Therefore, any conclusions drawn at this early date will have to be considered preliminary. However, the complexity of the coastal system, plus the unusually large quantity of oil, provided a hitherto unequaled opportunity to learn about the behavior of spilled oil in the coastal zone.

4.10.1 Influence of Coastal Processes and Coastal Morphology

Oil Dispersal Processes

The spill of the Amoco Cadiz provided a classic field experiment for the demonstration of the effects of dynamic coastal processes and coastal morphology on oil deposition along the coast. Strong, almost unidirectional winds from the west rapidly forced the oil eastward during the first few days of the spill. The rugged and indented topography of the coast then played a major role in determining where the oil would be deposited. The shorelines facing west were hardest hit, whereas those facing east, particularly those within the larger embayments, were mostly unaffected. This process is depicted diagramatically in Fig. 4-64A. During early April, the dispersal pattern of the oil changed. Major oil accumulations were broken up and dispersed. Because of the wind shift at the beginning of April, the oil was spread far into

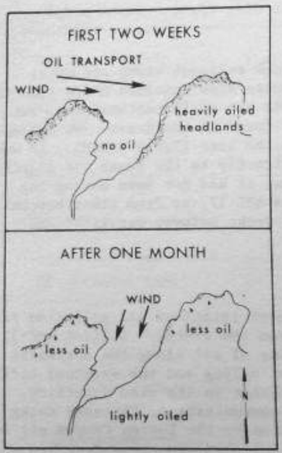


Figure 4-64. (Top) Oil pushed by strong westerly winds during the first two weeks was mainly deposited along westerly-facing headland areas. Interior embayments generally remained free of oil. (Bottom) A wind shift during the beginning of April spread a light layer of oil deep into the embayments. Previously deposited oil along the exposed headlands was greatly reduced in quantity.

many of the large embayments, thereby oiling previously clean areas. However, instead of single large oil masses, only thin bands of small mousse balls or oiled algae were deposited along the swash lines. Oil dispersal during this time period is illustrated in Fig. 4-64B.

Effects of Wave Action

During our earlier studies of the Metula and Urquiola oil spills, we observed that the degree to which an area is exposed to wave action greatly influences the longevity, or persistence, of oil within that area. Similar observations were made at the Amoco Cadiz site. Rocks heavily oiled south of Portsall were clean a short time later because of high wave energy at that locale. Many of the exposed environments along each northward jutting peninsula were generally free of oil within 1 month. Conversely, as wave energy decreases, oil persistence increases. Very little change in oil coverage was noted inside the harbor at Portsall, at Castel Meur (F-66), or at Primel-Trégastel (F-94). The marsh environment at Ile Grande illustrates an area with very low exposure to waves and, consequently, one with potential duration of oil effects.

Beaches vs. Sheltered Rocky Areas

In general, the sand beaches responded to natural cleansing much faster than sheltered rocky areas. Beaches undergo natural erosion and

depositional cycles in which large amounts of sediment are continuously reworked by waves. This action removes much of the oil within a relatively short period of time. In contrast, sheltered rocky areas and coarse-cobble beaches undergo change only during great storms. Also, oil seeping between rocks or into crevasses will be removed from direct wave attack. Thus, under similar conditions of wave exposure, a sand beach is much more likely to be cleaned by natural processes than is a rocky area.

Localized Geomorphic Controls of Oil Deposition

Within the areas receiving the oil, specific morphological features influenced the oil distribution pattern. Included among these features are (1) crenulate bays, (2) tombolos, (3) low-tide terrace, ridge, and runnel systems, (4) scour pits around boulders, and (5) regional bedding and joint patterns in the bedrock.

The catchment of oil by crenulate bays is illustrated in Fig. 4-65. Where crenulate bays occur on west-facing shorelines, as at Stations F-39, -62,-68 and AMC-9 and -17, they tend to trap oil at the head of the bay (northeast end), where the shoreline has its maximum curvature. The tail or southwest portion was usually free of oil during the first days of the spill (when winds were westerly).

Another morphological feature, the tombolo (Plate 4-21), also had a marked influence on the initial deposition of oil. As illustrated at stations AMC-5 and F-20, oil became trapped behind rocks or a small island because of the convergence of wave fronts around the offshore rocks. This process is illustrated in Fig. 4-66.

Other small-scale features that tended to cause localized oil deposition included scour pits around boulders, and jointing and bedding patterns in bedrock, both of which were observed at station AMC-13 (see Plates 4-16 and 4-17). An oil pond 5 cm deep was observed in a runnel on the low-tide terrace at station AMC-12.

Oil Response to Beach Cycles

Beaches undergo a cycle of erosion and deposition in response to changing wave conditions. By making repeated measurements of our permanent beach profiles, we were able to observe the effect of the beach cycle on erosion and retention of the oil. The recovery of the beaches (by berm formation) after the initial period of high wave activity (during the early days of the spill) commonly caused deep burial of oil layers in the beachface. The removal of 80% of the oil from the Roscoff area during two tidal cycles can be attributed partly to the erosional phase of the beach cycle. Therefore, a basic understanding of the beach cycle provides a good foundation for interpreting the behavior of oil on the beaches.

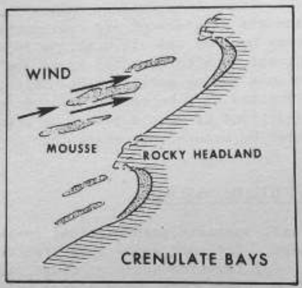


Figure 4-65. Entrapment of oil by crenulate bays. Generally, the southerly section of each bay remained free of oil.

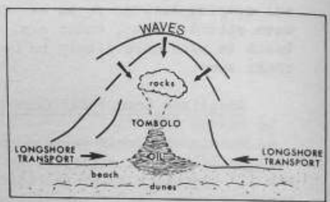


Figure 4-66. Illustration of the tombolo effect causing localized oil deposition behind offshore rocks.

4.10.2 The Vulnerability Index

On the basis of studies of the Metula and the Urquiola oil spills, we have developed the vulnerability index, a system of classifying coastal environments with respect to oil spill impacts (Hayes, Brown, and Michel, 1976; Gundlach and Hayes, 1978). The index is based mostly on predicted longevity of oil within each environment, but it has some biological criteria. Data derived from the study of this spill support some of our earlier conclusions and allow for further refinement of others.

Following is a summary of the oil spill vulnerability index with particular reference to the Amoco Cadiz oil spill. The order listed (1-10) is toward increasing vulnerability to oil spill damage; the higher the index value, the greater the long-term damage. A summary is presented in Table 4-21[8].

[8] It should be noted that the vulnerability index was developed in areas that could be readily classified as erosional or depositional. The Brittany coast presents a variety of sand beaches which show depositional cycles, but which, for the most part, are undergoing long-term erosion. Scarps of either bedrock or dune material occur back of most of the beaches, partly inhibiting formation of a truly depositional beach profile (which normally has a well-developed berm, berm-runnel, and back-beach area). This affects the classification system by somewhat limiting our original estimates of oil penetration and burial, and generally reducing the overall persistence of oil in these areas. Still, in terms of general oil persistence, the basic order of the index holds true.

Table 4-21. The Oil Spill Vulnerability Index with particular reference to the Amoco Cadiz oil spill. Higher index values indicate greater long-term damage by the spill. For further information, consult Hayes, Brown, and Michel (1976) or Gundlach and Hayes (1978).

Vulnerability Index	Shoreline Type; Example	Comments
1	Exposed rocky headlands; Douarnenez to Pte. du Raz and Primel-Trégastel to Locquirec	Wave reflection kept most of the oil offshore; no clean-up was needed.
2	Eroding wave-cut platforms; south of Portsall and F-1 to F-82	Exposed to high wave energy; initial oiling was removed within 10 days.
3	Fine-grained sand beaches; stations south of Roscoff (AMC-9 & 10) and east of Portsall (AMC-5)	All only lightly oil-covered after one month, mainly by new oil swashes.
4	Coarse-grained sand beaches; AMC-stations 4 (near Portsall) & 12 (St. Cava) and F-38	Oil coverage and burial after one month remains at moderate levels.
5	Exposed, compacted tidal flats; La Grève de St. Michel	No oil remained on the sand flat but did cause the enormous mortality of urchins and bivalves.
6	Mixed sand and gravel beaches; no really good example of this beach type	The index value is due to rapid oil burial and penetration; all areas had compacted subsurface which inhibited both actions.
7	Gravel beaches; stations F-80, 95 and 129, also AMC-16	Oil penetrated deeply (30 cm) into the sediment; clean-up by use of tractors to push gravel into surf zone seemed effective and not damaging to the beach.
8	Sheltered rocky coasts; common throughout the study area.	Thick pools of oil accumulated in these areas of reduced wave action; clean-up by hand and high pressure hoses removed some of the oil (this process is valid in non-biologically active areas.
9	Sheltered tidal flats; behind Ile Grande and at Castel Meur	Tidal flats were heavily oiled; clean-up activities removed major oil accumulations but left remaining oil deeply churned into the sediment; biological recovery has yet to be determined.
10	Salt marshes Ile Grande marsh	Extremely heavily oiled with up to 15 cm of pooled oil on the marsh surface; clean-up activities removed the thick oil accumulations but also trampled much of the area; biological recovery has yet to be determined.

(1) Exposed steeply dipping or cliffed rocky headlands

Two areas in particular fit into this category: (1) the cliff between Douarnenez and Pointe du Raz (Section I), and (2) the cliff between Primel-Trégastel and Locquirec (Section VII). In both areas, most of the oil was held approximately 10 m offshore by waves reflecting off the steep scarps. Some oiling did occur where reflected waves were dampened, as in small coves or pocket beaches. However, this is only a short-term condition since high-wave conditions will rapidly remove the oil.

(2) Eroding wave-cut platforms

A good example of this coastal type is located along the exposed coast between Trémazan (F-1) and Pointe de Landunvez (F-82) in Section II. Heavy oil accumulations that were originally found at Trémazan rapidly dissipated under repeated wave attack.

(3) Flat fine-grained sandy beaches

Fine-sand beaches are located to the southwest of Roscoff (stations AMC-9, AMC-10, F-17,-18 and-20) and to the east of Portsall (AMC-5). Each has a very broad beach/low-tide terrace. The beach profile is essentially flat. Within 1 month after being heavily oiled, each was categorized as having a light oil coverage, usually with only a minor oiled swash line. Cleanup activities at AMC-5 appeared to have caused little damage.

(4) Steeper, medium- to coarse-sand beaches

Beaches at stations AMC-4 and AMC-12 provide good examples of heavily oiled coarse-sand beaches. One month after heavy oiling, each still contained moderate to heavy oiling. Overall recovery was somewhat slower than at areas with index values of 1 to 3. Much of the beachface still contained oil or was oil-stained. Burial was also more common, but somewhat inhibited by underlying relict marsh or compact sandy gravel material. Again, this illustrates the complexity of the Brittany coast with regard to its erosional history. The coarse-sand beach at F-38, with no underlying base material, had 70 cm of oil burial.

(5) Exposed, compacted tidal flats

The large sand flat at St. Michel-en-Grève falls under this classification. Most of the oil was pushed across the tidal flat onto the beach at its edge. The flat itself was not significantly oiled; however, the enormous biological destruction caused by the oil supports its central position on this list. Perhaps, in terms of a truly biologically oriented oil spill index, this type of environment should be placed higher.

(6) Mixed sand and gravel beaches

There were no truly depositional mixed sand and gravel beaches in the spill area. Our original designation of this beach type as (6) was based on expected deep oil penetration. Each mixed sand and gravel beach in the spill area (AMC stations 1, 2, 6, 8 and 17) had an underlying material of compacted sediments that totally prevented oil penetration. Of these beaches, three were heavily oiled after 1 month, but two had only light coverage. The difference in remaining oil content is more attributable to variations in wave energy than to sediment type.

(7) Gravel beaches

All gravel beaches of the area remained heavily oiled 1 month after the spill. Typical examples are provided at F-stations 80, 95, and 129 and at AMC-16. In each case, oil penetrated deep into the beach sediment. Had cleanup not been started, it could be expected that the sediments would have become cemented together as the mousse turned to asphalt. This process was observed at the Metula site where no cleanup took place (Hayes and Gundlach, 1975).

(8) Sheltered rocky coasts

After 1 month, many sheltered rocky areas remained heavily oiled. Cleanup by hand and bucket and with water under high pressure reduces the amount of oiling but it is a slow and very tedious process.

(9) Sheltered estuarine tidal flats

Examples of this environment type are best illustrated by the sheltered environments behind Ile Grande and at Castel Meur (F-66). Oil coverage at both localities was exceedingly heavy. Clean-up activities succeeded in removing 80%-90% of the oil on the surface, but also extensively dug up the tidal flat. A large quantity of oil remains mixed into the sediment, and the interstitial water remains severely contaminated. The biological recovery of each area should be monitored.

(10) Sheltered estuarine salt marshes

The marsh at Ile Grande provides a classic example of the worst effects of an oil spill. A very extensive cleanup removed most of the 5 to 15 cm of pooled oil from the marsh, but overall biological recovery cannot yet be guaranteed.

Summary

Although the coastline of Brittany is exceedingly complex, the vulnerability index of coastal environments to oil spill damage, which was developed through studies at other spill sites, would have predicted the short-term behavior of Amoco Cadiz oil in each environment reasonably well. Environments rated high on the scale generally remain more highly oiled today (and generally represent more severe environmental damage) than those areas with low values. Thus the utility and application of this scale as part of a contingency plan for threatened areas (e.g., the coast of Alaska) seems to be clearly justified.

4.10.3 Oil Response to Tide-Level Changes

One of the questions raised by our previous oil spill studies (mainly those of the Metula and Urquiola spills) is whether the oil lifts off the bottom with every flood tide or instead becomes sediment-logged and remains on the bottom. At Portsall (AMC-1) and Les Dunes-East (AMC-5), we monitored oil reaction during a flooding tide. At AMC-5, we also watched oil reaction during the ebb cycle. During the initial oiling, the first week after the grounding, oil definitely lifted off with the incoming tide, and was redeposited on the ebb. However, during the second study period of late April, a large patch of sediment-bound oil was found on the tidal flat at Portsall. Some oil had mixed with the sediment and had sunk. Therefore, as has been hypothesized by others, a possibly significant percentage of the oil spilled by the Amoco Cadiz may have actually sunk to the bottom.

4.10.4 Oil Contamination of Interstitial Ground Water

After visiting a number of oiled areas, it became obvious to us that the problem of oil contamination of the ground water within the beach may be a cause of death to organisms living within the sediment. In many sites, even though the surface of the beach or tidal flat appeared completely clean, the interstitial ground water was severely oiled. Localities such as Portsall (AMC-1), Roscoff (AMC-6), and St. Michel-en-Grève (F-55) provide typical examples.

The ground water within a beach rises and falls with each tidal cycle. On the receding tide, large quantities of the ground water flow out of the beach, creating a series of ground water rills. However, a significant portion remains tied up within the sediment by capillary forces.

Oil may enter the ground water directly from the ocean water itself or through solution along the upper part of the beach. Contaminated ground water has an obvious oil sheen and often has visible droplets of mousse. If the concentration of oil in the ground water reaches lethal proportions, then death of infauna (cockles, heart urchins, razor clams and worms) may result, even though the surface of the area is not visibly oiled.

A question that remains to be answered concerns the longevity of this type of oil contamination: Is the ground water periodically flushed clean, or will it remain contaminated for months or even years?

Unfortunately, some of the methods now being employed to clean up the beach undoubtedly intensify the pollution of the ground water by the oil. The digging of large pits and trenches into the beach surface to use as catchment basins, such as those we witnessed at St. Michel-en-Grève, can only increase the contamination. Follow-up studies of beach processes and water chemistry are needed for a better understanding of this problem.

4.10.5 Cleanup Activities

Our perspective of the cleanup operation is from a geomorphological standpoint and not from the technical side. (See Chapter 6 for details on engineering techniques.) We are fortunate that our co-participant, Dr. Laurent D'Ozouville, has maintained contact with the Department of Equipment concerning the types of cleanup operations in force. Our combined suggestions follow:

(1) Restrict vehicular traffic on the beach, especially on the low-tide terrace. Oil often became deeply churned into the sediment as a result of heavy tractor usage. If tractors and trucks must be used, a single lane of traffic should be utilized.

(2) The removal of oil by manually scraping the surface layer with wood squeegees into trenches, to be suctioned off, is a valid method. However, natural infilling after abandonment of the pit often caused the deep burial of large amounts of oil. This oiled sediment should be dug up and placed in the surf zone so it can be cleaned by wave action. Long-term contamination of the interstitial water may otherwise result.

(3) The use of front-end loaders to scoop up thick layers of oiled sediment is valid in low-populated dune areas. This practice in areas that lack a readily replenishable sand supply may cause serious beach erosion problems. In general, any removal of sediment from the beach should be avoided.

(4) The use of bulldozers to plow oiled gravel into the surf zone is an excellent method for oil removal, because the sediment balance on the beach is maintained and the normal beach profile can be re-established by natural wave action.

(5) In general, the clean-up effort at Ile Grande marsh was laudable. The removal of oil from the marsh was necessary to establish any sort of biological recovery. The use of trenches to drain oil pools, as well as squeegees, buckets, and pressurized water, all seem valid from an environmental point of view. However, a problem

did arise by not limiting vehicles and personnel to certain access roads. The extensive walking and driving over the marsh may have further inhibited its recovery.

4.10.6 Where did the oil go?

Two of the primary questions usually raised during an oil spill are "Where did the oil go?" and "How did it change?". In a very basic attempt to answer these questions, we have made extrapolations from our areas of detailed study to the entire oil-affected coastline. This method has two weaknesses:

(1) Our study areas were generally limited to beaches. Thus, extrapolations to rocky areas may not be valid.

(2) We may be counting the same oil twice. For example, most of the oil within our Roscoff stations was removed by erosion on the night of March 24. This could be the same oil that we encountered in the Ile Grande area on March 29.

Calculations of oil coverage were made for the morphological sections (I-XI) of the coast during each of the two study periods. The results of this calculation are presented in Table 4-22. Using 17 of the 19 AMC stations as a basis (AMC stations 14 and 19 were eliminated), we calculated the average oil quantity per km of coast.

Table 4-22. Extent of oil coverage during study periods one and two. Oil is described as heavy only during study one (March 19-April 2). During study two (April 20-28), it is described as light or moderate-to-heavy.

Section of Coast	Study Period 1 (km oiled)	Study Period 2 km lightly oiled	km heavily oiled	total km of coastline
I	0	52	39	280
II	11	5	8	24
III	16	15	8	43
IV	4	30	0	38
V	4	43	0	43
VI	8	10	4	27
VII	4	24	9	76
VIII	9	10	20	35
IX	5	4	4	16
X	2	12	6	35
XI	9	8	9	36
Total	72	213	180	653

The results of these calculations are presented in Table 4-23. In order to determine the total amount of oil on the coast, the amount of oiled coastline (Table 4-22) was multiplied by the quantity of oil per km of coastline (as determined from the individual study sites; Table 4-23). The values used were 886.5 tons/km for all oiled areas during the first study, and 55.4 tons/km for moderately to heavily oiled areas, and 5.2 tons/km for lightly oiled areas during the second study. The results are presented in Table 4-24.

Table 4-23. Oil quantity per length of beach for 17 AMC stations during study period one (March 19-April 2) and study period two (April 20-28).

AMC-STATION	LENGTH OF BEACH	OIL CONTENT (metric tons) SESSION ONE	SESSION TWO Light Coverage	Heavy Coverage
1	500	50.2		7.3
2	250	1.8		2.4
3	250	44.6		5.5
4	200	284.1		2.5
5	1250	1146.9	2.5	
6	200	51.8	1.0	
7	200	102.5	1.7	
8	200	9.6	0.4	
9	2000	1039.4	10.6	
10	1250	46.3	6.0	
11	450	175.2		1.0
12	400	357.7		6.3
13	550	248.3	0.6	
15	300	83.3		3.9
16	400	81.2		66.3
17	300	136.4	1.6	
18	4000	7400.0		500.0*
SUB TOTAL	12.7 km	11259.1	24.4/4.7 km	595.2/10.75 km
TOTAL (metric tons)/km		886.5	5.2	55.4

*After clean-up

Table 4-24. Summary of data concerning shoreline coverage by oil and estimated total quantities for study sessions one and two.

	Session one (19 Mar - 2 Apr)	Session two (20 - 28 Apr)
km shoreline heavily oiled	72	180
km shoreline lightly oiled	-	213
total shoreline oiled km	72	393
total quantity of oil along shoreline	63,828 m tons	11080 m tons
	Total reduction between sessions = 83%	

During the first 2 weeks of the oil spill, a total of 72 km of coast was heavily oiled. Using our estimated quantity of oil per km of shoreline (886.5 tons) yields a total of 63,828 metric tons of oil (rounded to 64,000) that we are able to account for. This is approximately one-third of the total amount of oil lost from the tanker. The remaining two-thirds must be accounted for by evaporation loss, oil masses remaining on the water's surface, sinking to the bottom, and mixing into the water column.

During the second study session, 213 km of coastline were lightly oiled and 107 km were heavily oiled. Using our oil estimates for session two (Table 4-22), we can account for 10,310 metric tons of oil (a loss of 84% of the oil on shore during the first visit). This continued loss of oil from the shore can be attributed to a combination of natural cleaning processes and a very active cleanup program.

In conclusion, approximately one-third of the oil spilled from the Amoco Cadiz (estimated at 64,000 metric tons) went aground on 72 km of shoreline during the first 2 weeks of the spill. During the following 3 weeks, the quantity of oil along the shoreline was reduced by 84% (to approximately 10,310 metric tons). This reduction was due to natural dispersion and to cleanup activities by man. On the other hand, the amount of shoreline visibly contaminated by the oil increased to 320 km by late April. This increase was due to the break-down and dispersion of the large oil masses by waves and currents and to a major shift in wind direction (from westerlies to easterlies).

4.11 References

Chassé, Claude J. M. (1972): Economie sedimentaire et biologique (production) des estrans meubles des cotes de Bretagne: Thèse, L'Université de Paris VI, 293 pp.

Debelmas, Jacques (1974): Geologie de La France: Vol. 1 - Vieux Massifs et Grands Bassins Sedimentaires: DOIN Editeurs, 8, Place de l'Odeon, 75006 - Paris, 293 pp.

de Martonne, Emm. (1903): Le développement des côtes bretonnes et leur étude morphologique: Bull. Soc. Sc. Medic. Ouest (Rennes), 12:244-260.

de Martonne, Emm. (1906): La peneplaine et les côtes bretonnes: Ann. Geog., 15:299-328.

Emery, K. O. (1961): A simple method of measuring beach profiles: Limn. and Ocean., 6:90-93.

Folk, R. L. (1968): Petrology of sedimentary rocks: Hemphill's, Austin, Texas, 170 pp.

Guilcher, André (1948): Le relief de la Bretagne meridionale de la Baie de Douarnenez à LaVilaine: Thèse, L'Université de Paris.

Guilcher, Andre (1958): Coastal and submarine morphology: translated by B. W. Sparks and Rev. R. H. W. Kneese, Methuen & Co., Ltd., London, 274 pp.

Gundlach, E. R., and M. O. Hayes (1978): Vulnerability of coastal environments to oil spill impacts: accepted for publication by Marine Tech. Soc. Jour.

Hayes, M. O., E. H. Owens, D. K. Hubbard, and R. W. Abele (1973): Investigations of form and processes in the coastal zone: in Coastal Geomorphology (D. R. Coates, ed.), Proc. Third Ann. Geomorph. Symp., Binghampton, New York, 11-41.

Hayes, M. O., and E. R. Gundlach (1975): Coastal geomorphology and sedimentation of the Metula oil spill site in the Straits of Magellan: Final report to NSF-RANN, Coastal Research Division, Dept. of Geology, University of South Carolina, Columbia, South Carolina, 103 pp.

Hayes, M. O., P. J. Brown, and J. Michel (1976a): Coastal morphology and sedimentation, Lower Cook Inlet, Alaska: with emphasis on potential oil spill impacts: Tech. Rept. No. 12-CRD, Coastal Research Division, Dept. of Geology, University of South Carolina, 107 pp.

Hayes, M. O., C. H. Ruby, M. F. Stephen, and S. J. Wilson (1976b): Geomorphology of the southern coast of Alaska: 15th Conf. on Coastal Eng., Proc., 2:1992-2008.

5. BIOLOGICAL OBSERVATIONS

F. A. Cross,[1] W. P. Davis,[2] D. E. Hoss,[1] and D. A. Wolfe[3]

This report is a compilation of our own observations and data, combined with those of other NOAA/EPA specialists, and also includes information obtained from investigators at the Centre Oceanologique de Bretagne (COB), the Université de Bretagne Occidental (UBO), the Station Biologique Roscoff, and others as noted. Observations by U.S. biologists began March 26 following briefings from the NOAA Spilled Oil Research Team which had been conducting overflights and beach surveys since March 19--two days after the Amoco Cadiz went aground.

The information presented in this chapter does not reflect the results of a pre-planned biological study. Instead, predominantly qualitative observations were made by NOAA/EPA biologists from late March until late May while observing the development of French programs designed to assess the biological impact of the spill.

During this time, selected sites were chosen to develop familiarity with the diverse ecological habitats involved and to gather as much early event information as possible in an effort to obtain a general understanding of the effects of the oil spill on marine organisms including commercial species. These activities included (1) observing and photographing biological effects along the coast and, in some instances, making repeated observations at the same site over a period of about six weeks, (2) visiting two bird hospitals and a marine bird sanctuary, and (3) conducting interviews with representatives of various segments of the fishing industry. The geographical range of observations extended from le Conquet to Perros-Guirec--a distance of approximately 200 kilometers by coastline. In addition, a quantitative study on benthic organisms from three typical intertidal habitats was conducted by Jeff Hyland of the EPA, and his report is appended to this chapter.

We hope that the following information will serve as a reference to assist in planning for ecological impact assessment research on oil spills and will prove useful until more in-depth collaborative studies by French, Canadian, and U.S. scientists are completed.

---

[1]NOAA/NMFS, Southeast Fisheries Center, Beaufort Laboratory, Beaufort, NC 28516.
[2]U.S. EPA/ERL, Bears Bluff Field Station, Johns Island, SC 29455.
[3]NOAA/ERL, OCSEAP, Boulder, CO 80302.

5.1 General Field Observations

5.1.1. Impact on Intertidal Communities

The portion of the Brittany coast impacted by the oil spill consists of diverse ecological habitats and biological communities, including exposed sandy beaches, rocky headlands, protected bays, estuaries, and marshes. Biological communities in all these habitats were subjected to stress by the oil.

As discussed in the previous chapter, shorelines facing westward were the first to be oiled and received the largest amounts. Although wave action effectively "cleaned" or removed much of the oil from exposed rocks on the open coast, a considerable amount of oil was trapped in tidal pools, or remained on macroalgae such as Ascophyllum, Pelvetiopsis, and Fucus which are attached to rocks. On exposed sandy beaches, oil often was covered by a layer of sand that gave the beach the appearance of being clean (see Plate 4-26). In reality the buried oil contaminated interstitial water throughout the entire area of impact, and a visible sheen could still be observed in the interstitial water in late May.

Impact of the oil on intertidal communities in general was quite severe (also see the Appendix, this chapter). As discussed above, macroalgae on exposed rocks tended to retain the oil long after it had been removed from bare rocks by wave action (Plates 5-1 and 6-10). In addition to potential adverse effects of the oil on the macroalgae, retention of oil by this material undoubtedly increased contact time between the oil and organisms living beneath the algae. Although many of the macroalgae had, at least, a thin coating of oil, they did not appear to be dead except in a few areas that were extensively and repeatedly oiled, such as the upper intertidal beaches directly inshore from the wreck. More chronic effects may be occurring, however, as several preliminary bioassays by R. Steele on these plants indicate that the fertilization process failed to occur in exposed algae (EPA Progress Report on Amoco Cadiz Oil Spill, May 2, 1978). In previous work Steele (1977) found that exposure to crude oil prevented germination in Fucus edentatus. In addition, preliminary studies by scientists at COB indicate that growth of some macroalgae (Laminaria) has been affected by exposure to oil, and erosion of the edges of the blades of these plants has been observed.

Adverse effects from exposure to oil were noted on limpets (Patella vulgata and P. aspera) over most of the impacted coastline. We observed limpets with shells covered with oil (Plate 5-3) as well as limpets in a recently dead or moribund condition. As seen in Plate 5-5, mousse was trapped under the shell and retained there even after the surrounding rock had been cleansed by wave action or clean-up operations. The oil trapped under the shell caused these animals to lose contact with the rock, fall onto the sand and die, after which many of them were eaten by

seagulls (Plate 5-4). This sequence of observations was not uncommon, and the sensitivity of limpets to oil has also been noted by other investigators (Baker et al., 1977).

Nearly complete mortality of limpets and periwinkles occurred in the rocky intertidal zone immediately inshore of the wreck, just north of Portsall. At most other locations, however, live limpets, many heavily oiled on the shell, could still be found 5 to 8 weeks after the spill. Many of the oiled limpets had moved to tidepools where the rock surfaces had not been oiled. At Roscoff there was clear evidence by May 20 that the limpets were grazing over lightly oiled rocks and contributing to the cleanup process.

As the oil penetrated into the sand, molluscs and polychaetes emerged to the surface where they were more susceptible to wave action and predators (Plates 5-2 and 5-6). Live cockles (Cerastoderma-Cardium edule), in particular, were observed on the surface in sandy environments all along the affected coast. The valves of many of these animals could be pulled apart easily, which indicated their weakened condition prior to death.

The mortality of intertidal organisms (e.g., cockles, limpets and snails, Littorina), in general, did not occur as soon as mousse entered their environment but was observed over a period of two months following the wreck. Heaviest mortalities probably occurred in the first 2 to 3 weeks. Six to 8 weeks after the spill most of the heavily impacted, sandy beaches had undergone extensive cleaning both from the concentrated efforts of cleaning crews and from tidal and wave action. Large numbers of dead and moribund organisms were not seen at this time and many of the sandy intertidal areas appeared superficially "normal". Large numbers of Arenicola marina could be found actively extruding fecal matter from their burrows on most beaches. At two sites, however, we attempted to locate other living infaunal organisms with little success. On the beach at Dunes de Ste. Marguerite (AMC-11)* on May 7, 5 to 6 square meters were raked by hand for cockles and clams. None were found, although the dead shells on the beach suggested that they had previously been present in large numbers. Identical sampling of a similar but unaffected area on the south coast of Brittany produced 3 to 20 cockles per square meter along with associated clams (mainly Venerupis aurea).

Exceptions to these observations did occur. The beach at St. Efflam is one notable example which is discussed later in this chapter. The intertidal sand beach at Corn ar Gazel, which was sampled for species composition of infauna, is another (see Appendix, this chapter). On March 31 the water of this embayment had a strong odor of oil and was

---

*AMC designations represent geological stations; see Fig. 3-1.

milky-colored. A variety of freshly killed or moribund organisms was found (see Fig. 5A-1, Appendix), the most notable of which was Arenicola marina. Several individuals of this species were observed extending part-way out of the sand, yet Arenicola has been generally shown to be resistant to at least low concentrations of oil (Gordon et al. 1978, Baker et al. 1977).

The acute situation at Corn ar Gazel may have been related to the recent use of dispersants since the milky color of the water could have been due to droplets of emulsified oil. This milky water was very localized; a small embayment less than one-half kilometer to the west had normal-looking seawater, and relatively few dead organisms were observed. Although it is possible that the milky water came from offshore where ships of the French Navy were actively discharging dispersants, these chemicals were also used by clean-up crews along the shore. In late April, a clean-up crew was observed using dispersants and the nearby water turned a milky color that could still be seen several hours later. Clean-up crews also had been working on the beach at Corn ar Gazel just prior to our arrival and may have been using dispersants as well.

We observed dispersants being used to clean seawalls at Roscoff on April 1 and rocks near Santec on April 8 and between Ploumanac'h and Perros-Guirec on April 30. The operation at Roscoff consisted of men spraying the solution from canisters strapped to their backs prior to washing with water under high pressure. From discussions with the clean-up crew we learned that a much stronger dispersant had been used earlier but it irritated their eyes and skin and they had switched to a milder one. With this milder dispersant it was often necessary to use two treatments to remove the oil. On the beach directly below this cleaning operation, dead and dying cockles, nereid polychaetes, and periwinkles were observed. To what extent the use of dispersants contributed to these mortalities is not known, but the toxicity of dispersants and dispersant-oil mixtures has been previously documented (Wilson, 1974; Nelson-Smith, 1968; Smith, 1968). Near Santec and Ploumanac'h, firetrucks containing mixtures of water and dispersants were being used. An empty drum at Santec was labeled Treatolite demulsifer, Petrolite Corporation, London.

In some locations, part of the observed mortality could probably be related to cleanup activities. For example, intertidal rocks on the beach at Meis-Vran had been cleaned prior to May 7 with water under high pressure or more probably with steam. These rocks retained none of the typical molluscan fauna. Shell of limpets (Patella), periwinkles (Littorina), and trochid snails (Gibbula and Monodonta) were washed into drift rows streaming down from the rocks into the adjacent sand. In the lower part of the intertidal zone, however, limpets were still living beneath seaweed attached to rocks.

Other mortalities were related to specific events. Large kills of amphipods (Talitrus saltator) were observed by the geological team at several locations. These kills can be related to the spring tides in late March which deposited oil high on the beach or at the base of dunes, thus impacting the habitat of this species on a single occasion (see Plate 4-24).

The extent of petroleum impact on more protected environments such as estuaries, bays, and marshes was determined primarily by the configuration of the coastline. Estuaries or bays facing west were much more heavily impacted by oil than those facing east (see Chapter 4). The Aber Benoit and Aber Wrac'h estuaries near the wreck site and Rulosquet marsh at Ile Grande (AMC-18), about 90 kilometers by air from the wreck, acted as catchment basins, and relatively large volumes of oil were funneled into these habitats (see Chapter 3 for results of chemical analyses).

Rulosquet marsh at Ile Grande, the beach at St. Efflam, and the Aber Benoit estuary, were the most impacted environments observed. A description of the extent of oiling in the marsh and associated biological communities is given in Chapter 4 and the Appendix to this chapter (also see Plates 4-1 and 6-16). Observations made on March 30 indicated that the entire community of the macrofauna was in the process of dying since the entire marsh was covered with a thick layer of oil. Crabs (Carcinus maenus), polychaetes (Nereis diversicolor), and cockles were the most abundant animals affected (Plate 5-7). Still live but heavily oiled crabs sought refuge on seagrasses and debris and were sluggish upon being touched. Polychaetes were emerging from the sediments and attempting to remain in small patches of unoiled seawater (Plate 5-8) but often were observed struggling in the oil. Three days later (April 2) the NOAA geological team revisited the marsh and it appeared that virtually complete mortality of macrofauna had occurred. Thousands of dead polychaetes were observed in small saltwater pools contained within larger pools of oil (Plate 5-9), and many dead crabs were on the marsh surface. Live, struggling animals were not observed as on March 30. (For additional description of these observations, see Chapter 4.) Initially we considered this location as an area for potential study of long-term effects of oiling on marsh ecosystems. Studies will not be possible at Ile Grande, however, since cleaning crews have removed the top 20 to 25 cm of marsh over most of the affected area. This removal started on April 30 and was done with heavy equipment which generally excavated the marsh plants including the entire root system, leaving a bare sand-clay surface. On May 19 the marsh was revisited, and at this time, heavily oiled high marsh grass (Juncus?) was observed around the perimeter of the excavated area. Many of these plants had 4 to 6 cm of new bright green growth beneath the blackened and dead oiled portion of the stem.

The most dramatic biological effects of the oil spill that were observed occurred along a sandy beach near the village of St. Efflam on

April 2. This beach is located on the western side of an embayment (Lieue de Grève) approximately 84 km by air from the wreck site. The geological station (AMC-15) is on the eastern side of this same embayment near St. Michel-en-Grève. On April 2, approximately 2½ km of beach at low tide were covered by seven swash lines of dead organisms, predominantly urchins and molluscs, which extended for several hundred meters from the high tide line seaward (Plates 5-10 and 5-11; see also Plates 4-6 and 4-7). These organisms consisted primarily of tests of heart urchins (Echinocardium cordatum), razor clams (Ensis siliqua and Pharus legumen), cockles, and small surf clams (Mactra cinerea). In addition, many polychaete tubes (similar to Diopatra along the east coast of the United States) were found along the lower swash lines.

Several attempts were made to quantify the extent of mortality. One approach was to mark off one-square-meter sections in several swash lines and count all dead organisms within each square (e.g., Plate 5-12). Because the animals were not evenly distributed along the swash lines, we attempted to select areas that appeared to represent average concentrations of dead organisms within a swash line. One square meter that was counted contained 93 urchins, 52 razor clams, 75 cockles, and 39 surf clams. Another square meter yielded 14 razor clams, 33 surf clams, 56 cockles, and numerous worm tubes that we did not count. Other organisms also present along the beach but in lesser numbers included mussels (Mytilus edulis), small clams (Venerupis decussata, Venerupis pullastra, Tellina tenuis and Lutraria lutraria) and several unidentified tunicates. One dead cormorant was observed as well (Plate 5-13).

Three estimates of the number of dead organisms were made along this beach on April 2 by the NOAA team studying the effect of coastal processes on oil-sediment interaction. The following estimates appeared in the preliminary NOAA report on the Amoco Cadiz oil spill, Appendix B.

(1) "A swash line of dead heart urchins (Echinocardium sp.) 300 m long and 25 m wide was counted, based on the number of dead organisms occurring within a one-meter wide swath measured perpendicular to the swash line. The total arrived at was 120,000 dead urchins within that one swash line."

(2) "A swash line made up predominantly of dead razor clams 250 m long and 6 m wide was also measured using the same method as in (1). According to our estimate, there were 45,000 dead razor clams within that single swash line."

(3) "At evening low tide (7:00 p.m.) on April 2, the entire intertidal area was littered with shells of dead organisms. As the tide fell, a cover of approximately 3 to 5 dead organisms/m^2 was left behind. Heart urchins were by far the dominant species. At that time, the intertidal zone was measured to be 570 m wide. Assuming that each square meter contained 4 dead urchins (based on several counts), a 500 m

long section of the beach would have contained 1,140,000 dead urchins. Therefore, several million dead urchins were present on the surface of the intertidal zone at that time, in addition to hundreds of thousands of dead clams and worms."

In contrast to these massive mortalities, deposit-feeding polychaetes (probably Arenicola) appeared to have tolerated the elevated levels of hydrocarbons. Relatively high populations of these worms were actively pumping fecal material onto the surface of the sand in the region between the last swash line and the low water mark. An estimate placed their abundance at $15/m^2$. This observation was not unique to this beach; we also observed active deposit-feeding polychaetes on beaches where cockles and clams, in the process of dying, were emerging from the sand.

Although this kill was observed 16 days after the wreck, there is evidence that suggests that the die-off was recent and catastrophic in nature. This same beach had been visited at low tide by NOAA and EPA scientists on March 28 and on March 30, and this massive mortality was not then observed. We were told of the kill on April 1 while in Roscoff, so several million dead organisms were washed up on the beach over a 2 to 3 day period. Many of the dead molluscs had soft body tissues still attached to the shells (Plate 5-13); others appeared normal except that the valves could be pulled easily apart.

On a follow-up trip made to the same beach on April 14, freshly dead clams were found, indicating that mortality was continuing among the clam populations. In addition, some mussels were observed to be dead or dying in the area at this time. Thousands of tests of dead heart urchins and the shells of razor clams were still present, but it was obvious that they had been dead for some time and no freshly killed specimens were observed. The polychaete population, on the other hand, appeared not to be acutely affected, as indicated by the large number of mounds of fresh fecal material in the lower tidal areas.

By April 30, clean-up crews and wave and tidal action had removed nearly all traces of this earlier mortality from the beach. Only occasional urchin tests and razor clam shells could be found, half buried in the sand. Shells of the clam, Tellina tenuis, with the ligaments still intact, were abundant. Several shovelfuls of sand were shifted by hand and only one live Tellina was found.

The onset of mortalities in the St. Efflam area could have been triggered at least two ways. First, this region received massive amounts of oil that were trapped by the coastline extending from St. Michel-en-Grève to Perros-Guirec. Retention of oil in these waters, particularly the Bay of Lannion, was probably high and a latent period was required for the dissolved concentrations of hydrocarbons to reach toxic levels, mix to the bottom (which may have been to depths of 40 to 60 m), and penetrate into the sediment. The other possibility is that the use of dispersants in coastal waters accelerated the dissolution and vertical movement of the oil. Whatever the cause, oil was effectively mixed to the bottom in the Bay of Lannion; large numbers of dead urchins were photographed at 20 m depth during cruises of the CNEXO/COB ship R/V Thalia, and grab samples of sediment from this same area had extremely high concentrations of total hydrocarbons (Dr. L. Laubier, personal communication).

The presence of polychaete tubes on the beach may have been caused by physical processes rather than by toxicity. The tubes appeared to have been broken or torn with the top portion being transported to the beach. Such an occurrence can be more easily explained as resulting from the heavy wave action that pounded the coast following the wreck than from toxic effects of the oil. We would not expect the latter process to result in the breaking of the parchment-like tubes.

This area of the coast is the site of proposed long-term studies by scientists at UBO and COB. Dr. C. Chassé (UBO) had previously conducted an intensive ecological study of benthic fauna at Lieue de Grève as part of a doctoral dissertation (Chassé, 1972) that will provide baseline information for future studies. In addition, scientists at COB have begun to obtain quantitative data on benthic fauna in the Bay of Lannion, as well as to photograph benthic epifauna and measure hydrocarbon levels in the water and sediments at regular intervals.

5.1.2 Impact on Marine Bird Populations

The oil spill occurred at a time of year when many species of marine birds were in the process of migrating to summer nesting grounds. Some species that winter in this area were in the process of leaving (e.g., loons, ducks); other species that winter to the south or at sea (e.g., gannets and auks) were arriving to begin the nesting season. Two organizations were responsible for tabulating kills by species (Plate 5-15) as well as operating bird hospitals to treat live oiled birds. The Societé pour l'Etude et la Protection de la Nature en Bretagne (S.E.P.N.B.), associated with UBO, was responsible for coastline west of Locquirec, and the Ligue Francaise pour la Protection des Oiseaux (L.P.O.), a private organization, was responsible for coastline east of Locquirec.

The tabulated kill by April 14 was about 3,200 birds consisting of about 33 species. Four species, however, accounted for about 90% of the kill reported by S.E.P.N.B. and 80% of the kill reported by L.P.O. (Table 5-1) (S.E.P.N.B. and L.P.O., personal communication). These four species consisted of the razorbill (*Alca torda*), the guillemot (*Uria salge*), the puffin (*Fratercula arctica*) and the shag or cormorant (*Phalacrocorax aristotelis*).

Table 5-1. Predominant species of birds impacted by oil as of April 14-16, 1978.

Species	Reporting Organization			
	L.P.O.		S.E.P.N.B.	
	No. of Dead Birds	% of Tabulated Kill for All Species	No. of Dead Birds	% of Tabulated Kill for All Species
Guillemot	302	28	513	24
Shag	162	15	415	20
Razorbill	183	17	379	18
Puffin	205	19	679	32

Estimating the total kill of birds along the section of coast impacted by the oil, on the basis of the above figures, would be difficult for the following reasons:

(1) Variations in wind and current patterns following the wreck affected the numbers of birds brought ashore or carried to sea.

(2) Some parts of the coast are not readily accessible.

(3) An unknown number of birds reportedly were picked up in the clean-up operations and not tabulated.

(4) Species-specific behavioral patterns (e.g., those birds that spend most of their time swimming and diving rather than flying were most affected).

A potential chronic impact on marine bird populations may result from feeding on contaminated prey. Sea gulls were observed feeding on freshly-killed intertidal organisms at a number of locations along the coast. This was particularly true on sandy beaches or intertidal flats that were not heavily covered with oil. Shorebirds and seagulls were conspicuously absent, however, in areas heavily covered with oil, such as the Aber Benoit estuary and the marsh at Ile Grande, although many recently killed invertebrates were present on the sediment surface.

The single most important nesting area for marine birds within the area of impact is Les Sept Isles Bird Sanctuary. This sanctuary, composed of seven islands and many rocky outcroppings, is located about 3 miles off the coast of Brittany near the town of Perros-Guirec (Figs. 1-3 and 5-1). These islands, which are about 100 km by air from the wreck site, are a natural reserve under government control and are managed by L.P.O. They are restricted from human activity except for Ile Aux Moines, which can be visited only with special permission from L.P.O.

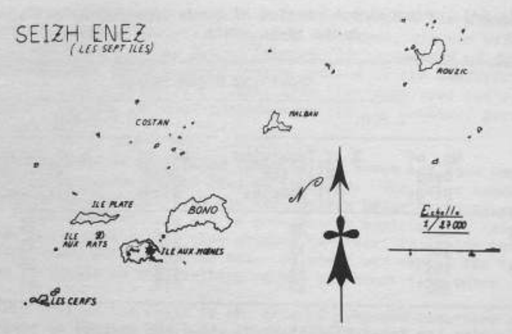


Figure 5-1. Islands constituting Les Sept Iles (From Milon, 1972).

Although many species of marine birds nest or feed on and around the islands, this sanctuary provides protection for three species of marine birds now considered rare or threatened in France. These are the puffin, the razorbill, and the guillemot, which represent three of the four most impacted species relative to total numbers of birds killed along the coast.

Two of the islands, Rouzic and Melban, support the southern-most nesting colony of the puffin in Europe (Plate 5-23). These islands are normally visited only once per year when two scientists conduct a census of nesting birds. Prior to the wreck of the Torrey Canyon, which occurred at the same time of year as the Amoco Cadiz, over 2000 nesting pairs of puffins inhabited these two islands. Some of the oil from the Torrey Canyon reached this section of the Brittany coast and the number of nesting pairs on these islands dropped dramatically the next year. It had stabilized at about 800 during the past several years.

Other marine birds that inhabit this sanctuary are the razorbill (less than 100 pairs), guillemots (about 300 pairs), kittiwakes (20-100 pairs), storm petrels, herring gulls, greater and lesser blackbacked gulls, and fulmars (100 pairs). After the Torrey Canyon incident the number of nesting razorbills and guillemots in this sanctuary also decreased sharply, from 250 to 90 and 400 to 150 breeding pairs respectively (Milon, 1972).

This sanctuary received a considerable amount of oil since it was directly in the path of the main flow coming from the Amoco Cadiz. The occurrence of the spill at this time of year was unfortunate because

many of the birds, particularly puffins, were just arriving at the sanctuary from their wintering grounds. Upon arrival the puffins initially spend their time swimming and diving around the islands before moving onto them to nest. This behavior pattern made the species particularly susceptible to oiling.

We visited the sanctuary by boat on April 2 accompanied by two ornithologists from L.P.O. This was the first visit to the islands by L.P.O. since the wreck. High seas and a fear of scaring birds from the islands into the oil-covered water had prohibited earlier visits. According to our colleagues from L.P.O., 200 to 300 puffins would normally be present in the water or on rocks around Rouzic and Melban at this time of year. Only one puffin, however, was observed as we circled both islands, although several hundred dead puffins had been found along the mainland. It is not yet possible to know the impact of the oil on this nesting colony since the dead puffins found along the beach included members of other colonies that were in the process of migrating to more northern nesting grounds. As of April 14 more than 850 dead puffins had been reported (Table 5-1). What percentage these birds represent of the total puffin kill or of those that would have remained at Les Sept Iles is not known.

A gannet colony of about 4,000 breeding pairs also inhabits the island of Rouzic (Plate 5-14). These birds did not appear to be acutely affected by the oil spill. Only 2% of bird mortalities reported by S.E.P.N.B. were gannets. Potential chronic effects may exist for this population, however, since oil-contaminated debris and seaweed may have been used to build nests.

Another likely mechanism for impact of the oil upon marine birds is the surface contamination of incubating eggs, either from fouled materials used for nesting or from contamination of the brood patch of the parent. Microliter quantities of fuel oil supplied to the surface of mallard and eider eggs caused significant mortality of embryos (Albers, 1977; Szaro and Albers, 1977), and similar results have been obtained with Alaskan crude oil or gull eggs (Patten and Patten, 1977). Furthermore the gulls tended the oiled eggs for an extended period and then abandoned their nests, failing to produce a second viable clutch. Evidence of such reduced hatching success should be watched for at Les Sept Iles.

Marine mammals also were affected by the oil in the vicinity of the sanctuary. In addition, a small population of grey seals inhabits the islands, and efforts are underway to determine if they are an independent reproducing colony. If so, it will be the second such colony along the coast of France. As of April 2 three dead seals were found along the northwest Brittany coast.

5.1.3 Potential Impact On Coastal Fisheries

The region of the Brittany coast impacted by the oil spill is one of both traditional and developing fisheries. Like most coastal fisheries, they are very diverse and the effect of the oil on them will be species-specific. The full impact may never be known. The nature of the effects will be complex and will vary from short-term impacts on population size and availability to fishermen to potential chronic effects on year-class. In addition, the future marketability of coastal fishery products with elevated levels of hydrocarbons is not known. In this section we will provide a brief overview of some of the more important fisheries along this part of the Brittany coast that may be impacted by the spill.

Coastal waters from Le Conquet to St. Malo support a diverse commercial fishery for seaweed, crabs, clams, oysters, scallops, and several species of finfish. Mariculture is important in the commercial production of some of these species. Fishermen operate out of several small ports along the coast (e.g., Le Conquet, Portsall, Brignogan, Roscoff, and Perros-Guirec).

The Amoco Cadiz went aground in an area where marine algae have been harvested for many years. This fishery is concentrated in coastal waters from Le Conquet to Brignogan (near AMC-14) and produces about 75% of the total seaweed harvest in France. The algae are harvested from the high tide mark to depths of 25 meters and consist primarily of Laminaria digitata, Laminaria flexicaulis, Fucus vesiculosus, Fucus serratus, and Ascophyllum nodosum. After the harvest the material is air-dried on meadows along the coast and shipped to factories for processing. Approximately 200 fishermen and 150 boats are involved in this fishery. One factory that we visited in Landerneau processed 6,000 dry metric tons per year and produced alginates, flours, powders and liquids for baths and shampoos, and a jelly used by the cosmetic industry.

The subtidal or Laminaria fishery harvests from 4,000 to 6,000 dry metric tons per year in a season from April 15 to September 30. The principal product is alginates which are used as thickening and stabilizing agents in foods and industrial products. During the first week of May, we observed Laminaria being unloaded from boats at l'Aber Wrac'h and at Roscoff. It is not known if this crop had been affected by accumulated oil from the Amoco Cadiz. Laminaria also has been traditionally gathered from the beaches at Santec (about 6 kilometers west of Roscoff) as it washes ashore in late spring and summer. On May 18, the beaches in this area had visible sheens of oil in the interstitial water, and small quantities of mousse were still coming ashore. Thus the harvest of this beached material also may be affected.

The attached algae in the intertidal zone (Fucus and Ascophyllum) are hand-picked at low tide or gathered on the beaches. The harvest is

estimated at 6,000 to 7,000 dry metric tons per year, and is used primarily to produce a flour used as a supplement for cattle feed.

Because of the location of the wreck, a significant portion of both the subtidal and intertidal algae important to the seaweed industry was exposed to large amounts of oil and its dissolved fractions. This exposure occurred just prior to the opening of the harvesting season, and the effects on the industry are now being determined in terms of growth, reproduction of plants, and accumulation of hydrocarbons. Large amounts of potentially harvestable seaweed were removed from the beaches during cleanup operations because of heavy oiling, particularly near Portsall. In the harbor of Portsall, oiled Fucus and Ascophyllum were systematically hand-picked in late May from intertidal rocks and jetties by military cleanup crews.

Adverse effects on the mollusc fishery will probably be most significant for oysters and clams. Rearing of oysters (Crassostrea gigas and Ostrea edulis) on racks is an important aspect of Brittany's shellfish industry, and several commercial operations were impacted by the spill. Most notable were those located in and just off the mouths of the Aber Benoit and Aber Wrac'h estuaries. As discussed earlier in this chapter, these estuaries received large amounts of oil because they were directly downwind from the wreck. Although some oysters were removed from gardens or holding pens prior to the arrival of oil, most of the crop was either killed or heavily contaminated both in the estuaries (Plate 5-16) and in adjacent waters (Plate 5-21). One dealer interviewed in St. Pabu on the Aber Benoit estuary stated that he had released 119 of 125 employees as of April 4. In the Aber Wrach estuary, oysters contained visible oil around the fringes of the mantle in mid to late May, and the oyster industry was still shut down. A dealer interviewed at that time indicated that he may be required to dispose of his remaining stock of contaminated oysters.

Another important culturing area is located in the Bay of Morlaix. Because it is farther from the wreck, dealers had time to remove and transport some of the oysters to beds in southern Brittany, although we understand that some mortalities and/or contamination of oysters did occur. We have no information at the present time relative to the total impact of the spill on the commercial oyster industry, nor the time that will be required for the re-establishment of an acceptable water quality.

In addition to the oyster culture operations, a small clam fishery is located at Perros-Guirec. We observed dead and dying clams of commercial importance (Venus verrucosa, Venerupis pullastra and Venerupis descussata) on beaches near Perros-Guirec, but do not know what the impact will be on this fishery.

The impact of the spill on the scallop (Argopecten) fishery may be minimal. This industry is centered in and near the Bay of St. Brieuc, which yields about 10,000 metric tons/year. This region was not heavily contaminated by the spill. A small scallop fishery (about 100 metric tons per year) is located in the Bay of Morlaix and could be affected. Divers from the Roscoff Biological Station have observed mousse on the bottom of the Bay of Morlaix. This could affect either the scallops themselves, or could interfere with fishing for them.

Two species of crab are fished in the impacted area, Cancer pagurus and Maia squinado (spider crab). As with the other fisheries, it is too early to assess effects. Spider crabs were in the process of migrating into shallower coastal waters when the spill occurred. In the nearshore areas between Roscoff and the Bay of Morlaix, many fishermen were observed running their traplines during May, and spider crabs were being landed at Roscoff and at Le Diben (2 km SSW of Pointe de Primel).

The Societé Langouste at Roscoff is a specialized commercial operation that deals primarily with lobsters (Plates 5-17 and 5-17a). It imports lobsters (both Homarus and Palinurus) from around the world (e.g., Canada, United States, South Africa, Brazil, Argentina), holds them in pens exposed to natural seawater, and sells several hundred tons per year to dealers in France. In addition, oysters and clams caught locally are held and sold depending on price fluctuations. The oil arrived at this facility at 2:00 a.m. on March 21 just 2 hours after all the lobsters were removed to tanks with a closed cycle recirculating system. An oil control boom was placed in front of the pens (Plate 5-17A) but high winds and tides drove the oil across the booms and into the pens (Plate 5-18). The oiling of this facility was so extensive that it is expected to be out of operation for at least a year. All wood will be replaced and oil will be burned off the concrete, which will then be recemented. Some spiny lobsters and oysters were being held in the closed recirculating system on the day of our visit (April 1) and the seawater was being transported from Brest by truck.

Although some fish, such as rock fish, gobies, and one species of gadidae (Plate 5-20), were killed within a 10 km radius of the ship-wreck, there is very little known as yet about the effects of the oil spill on the commercial fishery of the area. Few dead commercially-important fish, such as mullet, mackerel, pollock, bass or flatfish species, were collected. Flatfish such as plaice (Pleuronectes platessa) may suffer from adverse effects on year-class strength since larvae and juveniles were concentrated in estuaries and bays that were heavily oiled. What effect the oil suspended in the water column will have on the survival of the larvae of these species is unknown, but contamination at this critical phase could have serious consequences (Michael, 1977). Mackerel (Scomber scombrus), on the other hand, spawn elsewhere and migrate into these waters to feed during the spring and summer. Adverse effects on this species may be minimal except for possible food web contamination. In any case, there are few data on fishing effort in the impacted area, and this will make it difficult to determine impacts on coastal fisheries in future years. If significant quantities of oil

are present on the sediment in traditional fishing area, both gear and catch may be fouled and economic losses will be incurred. A fisherman at l'Aber Wrac'h indicated that gear fouling was a problem in offshore areas that he had fished in late April and early May.

5.1.4 Potential Impacts on Terrestrial Communities

Although we have focused upon marine communities, terrestrial communities must be considered as well. Volatile fractions of the petroleum, strongly evident to the human observer, caused dizziness, headaches, and nausea. The lobster dealer at Roscoff noted that song birds left that area 2 to 3 days before arrival of the oil. These birds may have been responding to the presence of air-borne hydrocarbons. They reportedly began to return 1 to 2 weeks later.

Transport of airborne fractions of petroleum to farm crops may have been substantial. In a few instances crops directly adjacent to the coast were oiled and had to be destroyed (Plate 5-19). The process of assimilation of volatile fractions of petroleum by crops and transport of measurable fractions of these compounds to humans either directly by consumption of the crops or indirectly by consumption of livestock may be unique to this oil spill.

5.1.5 False Color Photo Infrared Pictures

Infrared pictures were taken by the SOR team on an experimental basis as a possible aid in identifying beached oil and documenting changes in the flora. Kodak Ektachrome infrared film was used with a wratten #12 filter as recommended by Kodak for biological work. As seen in Plate 5-24a, Amoco Cadiz oil on the rocks and on the beach (not shown) appears greenish. Also apparently healthy Fucus can be seen in the background appearing red. In normal light, fucus and oil are hard to distinguish, especially from the air. Also, live and dead seaweed appear the same in normal light, whereas the "healthy" red color in infrared is lost when the plant dies. Most plants will show changes in infrared when under stress, before any change is detectable in normal light. Fig. 5-24b shows the greenish color of oil mixed with the red of the grass in the area that has been covered with oil.

5.2 Summary

Adverse biological effects of oil spilled from the Amoco Cadiz were observed along the northwest coast of Brittany ranging from Portsall to Perros-Guirec--a distance of about 150 km of coastline with numerous rocky outcroppings and islands. Habitats impacted by the spill consisted of exposed sandy beaches, rocky headlands, bays, estuaries, marshes, subtidal areas, and neretic waters. Biological communities in these habitats were subjected to varying degrees of stress depending upon type of habitat, distance from the spill, and location relative to the configuration of the coastline.

Intertidal communities on coastlines facing west, as well as the Aber-Benoit estuary and Rulosquet marsh near Ile Grande, were severely impacted by the petroleum. The effects were maximized by spring tides which occurred just after the wreck. Massive mortalities of intertidal communities occurred near St. Efflam and at Rulosquet marsh over a relatively short time (a few days) whereas mortalities of other populations were observed to occur more gradually (over several weeks). Populations of intertidal crabs, nereid worms, bivalve molluscs and limpets were much more acutely affected by the spill than was the deposit-feeding polychaete Arenicola. For epifauna, mortality appeared to be related to physical coating by the oil. The dissolved fraction of oil that penetrated into the interstitial water was probably the primary factor contributing to mortalities of infauna. Acute effects generally were not observed on attached macroalgae although some evidence obtained in an independent study indicated that the fertilization process of exposed plants may be impaired.

Extremely large concentrations of dead and dying organisms were observed at two locations 16 days after the wreck. On April 2, several million dead molluscs and urchins were present along 2½ km of beach near the village of St. Efflam. These organisms consisted primarily of heart urchins (Echinocardium cordatum), razor clams (Ensis siliqua and Pharus loguma), cockles (Cerastroderma edule) and surf clams (Mactra cinerea). At Rulosquet marsh near Ile Grande on the same day, thousands of dead polychaetes (Nereis diversicolor) and large numbers of dead crabs (Carcinus maenus) covered the marsh surface.

Although some fish kills were reported in the general vicinity of the wreck prior to the time our observations began (March 29), we rarely observed dead fish. Larval fish populations of certain species present in the area at the time may have been affected but the specific effects will be difficult to determine. Some fish species may become contaminated by the transfer of hydrocarbons through the food chain.

Dispersants, which were used both in coastal waters and in shoreline cleanup operations, may have contributed to the fish mortalities observed at Corn ar Gazel and St. Efflam. The use of dispersants in cleanup operations varied along the coast but they were used extensively near Roscoff in early April. To what extent these chemicals contributed to mortalities in intertidal areas is not known.

The oil spill occurred at a time when many species of marine birds were migrating from wintering to nesting grounds. Over 3,200 deaths were recorded which consisted of more than 30 species. About 85% of these deaths, however, consisted of four species (shag-cormorant, guillemot, razorbill, and puffin), the last three of which are considered rare or threatened in France. More chronic effects on marine birds may occur from feeding on contaminated prey. For example, seagulls were observed feeding on freshly killed intertidal organisms all along the impacted coastline.

The Sept Iles Bird Sanctuary near Perros-Guirec provides important nesting grounds for several species of marine birds along the northwest coast of Brittany, particularly for puffins, razorbills, and guillemots. Two islands in the sanctuary support the southernmost nesting colony of puffins in Europe. This colony was severely reduced as a result of the Torrey Canyon oil spill and may be further reduced by the Amoco Cadiz incident.

Coastal waters along the northern coast of Brittany support a diverse commercial fishery for seaweed, crabs, clams, oysters, scallops, and several species of finfish. The Amoco Cadiz went aground along the section of the coast that produces about 75% of the seaweed harvested in France. Both subtidal (Laminaria) and intertidal (Fucus and Ascophyllum) species were exposed to extremely high concentrations of oil just prior to the opening of the harvesting season. The effects on the industry are now being determined in terms of growth and reproduction of plants, and accumulation of hydrocarbons. Mariculture operations for oysters were severely affected in the Aber Benoit and Aber Wrac'h estuaries and the Bay of Morlaix. Large numbers of oysters were either killed or contaminated by the spill. The holding pens of the commercial lobster operation at Roscoff was heavily oiled and probably will be out of operation for a year. The main scallop fishery in Brittany is located east of the impacted area and adverse effects may be minimal. At the present time, we have no information on the impact of the spill on the crab industry.

Little is known as yet about the effect the oil spill on the commercial finfish industry although few dead commercially-important fish were reported. Obviously those species whose young inhabit bays and estuaries (e.g., plaice) will probably be affected more severely than species that spawn in offshore waters and migrate into coastal waters to feed (e.g., mackerel).

The transport of oil or its volatile fractions to terrestrial communities may have been substantial. In late March gale-force winds and spring tides combined to deposit oil above the high tide mark. More importantly, some of the airborne fractions of the petroleum can adhere to plants and be transported to humans through farm crops or livestock.

A coordinated program to assess the biological consequences of the Amoco Cadiz oil spill is currently being developed by French scientists from Roscoff, UBO, and COB. For example, proposals have been made to study the repopulation of intertidal communities in areas where pre-spill baseline information exists; the occurrence of neoplasms in shellfish (some oysters and cockles were collected shortly after the spill for this purpose); the effects of the oil spill on the year-class strength of plaice; the effects of growth and reproduction of attached microalgae; and the accumulation of hydrocarbons by a variety of species including birds. In addition research programs between French scientists and scientists from other countries, such as the United States and Canada, have also been planned.

5.3 References

Ablers, P. H. (1977): The effects of external applications of fuel oil on hatchability of mallard eggs. In: (D. A. Wolfe, ed.). Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems, Pergamon Press, New York, 158-163.

Baker, J., J. Addy, B. Dicks, S. Hainsworth, D. Levell, G. Crapp, and S. Ottway (1977): Ecological effects of marine oil pollution. Rapp. P.-V. Reun., Cons. Int. Explor. Mer, 171:196-201.

Chassé, C. J. M. (1972): Economie, sedimentaire et biologique (production) de Bretagne. Ph.D. Thesis, Station Biologique de Roscoff, Faculty of Sciences, UBO. 293 p.

Gordon, D. C., Jr., J. Dale, and P. D. Keizer (1978): Importance of sediment working by the deposit-feeding polychaete Arenicola marina on the weathering rate of sediment-bound oil. J. Fish. Res. Board Can., 35:591-603.

Michael, A. D. (1977): The effects of petroleum hydrocarbons on marine populations and communities. In: (D. A. Wolfe, ed.), Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems, Pergamon, New York, 129-137.

Milon, P. (1972): La mort sur l'île, Crepin-Leblond et Cie, Paris, France, 107 p.

Nelson-Smith, A. (1968): The effects of oil pollution and emulsifier cleaning on shore life in southwest Britain. J. Appl. Ecol., 5:97-107.

Patten, S. M., Jr., and L. R. Patten (1977): Effects of petroleum exposure on hatching success and incubation behavior of the Gulf of Alaska herring gull group (Larus argentatus X Larus glaucenscens). NOAA Environmental Research Laboratories, OCSEAP Principal Investigator Reports, Boulder, Colo., 22 p.

Smith, J. E. (ed.) (1968): "Torrey Canyon" pollution and marine life, Cambridge Univ. Press, 196 p.

Steele, R. L. (1977): Effects of certain petroleum products on reproduction and growth of zygotes and juvenile stages of the alga Fucus edentatus de la Pyl (Phaeophyceae: Fucales). In: (D. A. Wolfe, ed.). Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems, Pergamon Press, New York, 138-142.

Szaro, R. C. and. P. H. Albers (1977): Effects of external application of No. 2 fuel oil on common eider eggs. In: (D. A. Wolfe, ed.). Fate and effects of Petroleum hydrocarbons in marine organisms and ecosystems. Pergamon Press, New York, 164-167.

Wilson, K. (1974): Toxicity testing for ranking oils and oil dispersants. In: (L. R. Beynon and E. B. Cornell, eds.). Ecological aspects of toxicity testing of oils and dispersants. Applied Science Publishers Ltd., Essex, England, 11-22.

APPENDIX, CH. 5

ONSHORE SURVEY OF MACROBENTHOS

Jeffrey L. Hyland*

Introduction

An onshore preliminary survey was conducted March 27 to March 31, 1978 along the northern Brittany coast from Argenton east to Ile Grande for the purpose of evaluating the extent of the oiling and the magnitude of onshore ecological impact. General ecological observations and photographs generated along route have been incorporated into various other sections of this report. The following section summarizes results relevant to two specific objectives: (1) to observe and photograph obviously oiled, dead, or moribund organisms found on contaminated beaches, and (2) to develop a general understanding of the spatial and numerical distribution of benthic macrofaunal species considered at risk. Results reflecting these two objectives are discussed for each of several habitats investigated.

Sampling Techniques and Treatment of Data

The types of habitat of research stations included an intertidal sandy cove with algal-coated rocky zones (Roscoff--EPA station 1); a salt marsh (Ile Grande-EPA station 2); and a high energy, ocean-exposed sandy beach backed by steep dunes (Corn ar Gazel--EPA station 3). Each station was photographed, and samples of dead, moribund, and oil-coated organisms were returned to the laboratory for gross observation and species identification.

Routine techniques of field sampling and data reduction were employed for describing the distribution of species at risk. Sampling was conducted during low tide, 3 to 5 days after the arrival of spring tides. In the rocky intertidal zone at Roscoff, density estimates of macroepifauna were made at five substations using 0.25 m^2 quadrats. The

*U.S. EPA/ERL, Narragansett, RI 02882.

macroinfauna was sampled at Roscoff from three additional sandy substations (high water mark on beach at Mariner's Home--substation 1-1; middle of cove between Roscoff and tip of Perharidic peninsula--substation 1-2; and low water mark at mouth of cove, near edge of channel between Roscoff and Ile de Batz--substation 1-3). The macroinfauna alone was sampled from one substation at Ile Grande (on a mud flat along southern edge of main channel intersecting highway D21) and from three sandy substations at Corn ar Gazel (10 m above low water mark--substation 3-1; low water mark--substation 3-2; and 5 m below low water mark--substation 3-3). Each infaunal substation was represented by 10 pooled, replicate samples collected with a 0.01 m^2 polyvinyl chloride corer to a depth of 20 cm and rough sieved through a 2.0 mm screen. Contents on the screen were preserved in a 10% formalin solution in the field and returned to the laboratory for identification and enumeration of all macroinvertebrates. Most organisms were identified to the species level with the aid of the following literature:

Polychaeta:	Fauvel (1923, 1927), Clark (1960), Day (1967)
Mollusca:	Cornet and Marche-Marchad (1951), Allen (1962), Tebble (1966)
Crustacea:	Sars (1890), Truchot and Toulmond (1964), Bourdon (1965), Allen (1967), Barnard (1969), Bouvier (1940), Chevereux and Fage (1925)

Other general works that were useful included Barrett and Yonge (1958), Eales (1967), Day (1969), and Gosner (1971). Data analysis included the generation of preliminary species lists with numerical abundances and the calculation of species diversity (H', in bits per individual) with its components, species richness (Gleason diversity, D_G) and evenness (J').

Additional samples of sediment and organisms were collected from each station for routine hydrocarbon analysis, the results of which are discussed elsewhere in this report.

Field work was facilitated through the services of Jim Lake (EPA, Narragansett, Rhode Island) and Bud Cross (NOAA, Beaufort, North Carolina). Taxonomic assistance was provided by Sheldon Pratt (U. of Rhode Island, Oceanography Dept.), Robert Bullock (U. of Rhode Island, Zoology Dept.) and John Scott (EPA, Narragansett, Rhode Island).

Rocky Intertidal Zone at Roscoff

Table 5A-1 lists macroepifaunal species identified and enumerated within the five rocky intertidal substations. The species are considered members of the mesolittoral zone and were found attached or crawling on bare rock or on dense patches of algae (mostly *Ascophyllum nodosum* and *Fucus* spp.) at approximately 0.5 to 1.5 m above the base of the substrate. The list includes only the obvious species that were large enough to recognize and enumerate in the field, and is therefore exclusive of the smaller organisms, particularly amphipods and small gastropods, associated with microhabitats. Limpets (Patella vulgata) and periwinkles (Littorina obtusata and L. littorea) were the most numerous. Other species included the gastropod, Gibbula umbilicalis; the chiton Lepidochitona cinereus; the tube dwelling polychaete, Spirorbis borealis; and the barnacle, Elminius modestus.

Table 5A-1. Species list for rocky intertidal quadrats at Roscoff.

Species	Quadrats (no.'s per 0.25 m^2)				
	1	2	3	4	5
Gastropoda					
Patella vulgata	2	-	4	16	16
Littorina obtusata	1	-	1	6	-
Littorina littorea	-	-	1	-	-
Gibbula umbilicalis	-	-	-	1	-
Polychaeta					
Spirorbis borealis	occasional calcareous tubes	2	-	occasional calcareous tubes	-
Amphineura					
Lepidochitona cinereus	-	-	1	-	-
Cirripedia					
Elminius modestus	-	-	dense population	-	-
Algae					
Mostly Ascophyllum nodosum & Fucus spp.	80 to 100% cover				

All species within these quadrats were exposed to the oil, because thick layers of oil were still heavily concentrated on the rocks and algae. Consequently, most organisms were considered at risk and some were in the process of being eliminated at the time the survey was conducted on March 29. Limpets and periwinkles, for example, were

particularly affected, and dead and moribund individuals were observed at the base of the rocks. Some limpets were beginning to lose purchase on the rocks and were easily removed with the flick of a finger. Limpets are unable to hold their shells firmly against the substrate for long periods of time, since the adductor muscles must relax occasionally allowing the shells to lift slightly. When this occurs in heavily oiled areas the oil may penetrate beneath the shell margin, thus contaminating the gills and other delicate tissues. Close examination of the limpets revealed contamination of the soft body parts and deterioration of the flesh. Shore birds were observed pecking the upturned shell contents.

Other epifaunal species not necessarily occurring within the five quadrats were found dead or moribund in the immediate vicinity. These included the topshells (Gibbula cineraria, G. umbilicalis, and Calliostoma zizyphinum) and the green crab (Carcinus maenus) (Fig. 5A-1). Close examination of dissected crabs revealed that the oil had formed a thick coating around the gills.

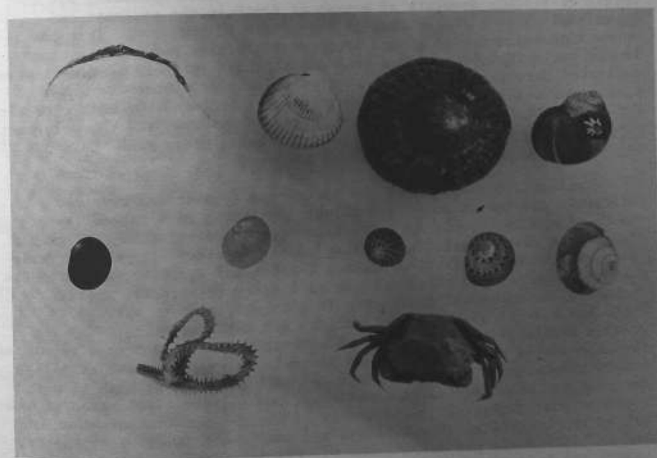


Figure 5A-1. Dead and moribund organisms at EPA Station 1, Roscoff. Left to right: Top-row--Venerupis descussata, Cardium edule, Patella vulgata, and Littorina littorea (with attached Elminius modestus). Middle row--Littorina obtusata (one black and one yellow specimen), Gibbula umbilicalis, Gibbula cineraria, and Calliostoma zizyphinum. Bottom row--Nereis diversicolor and Carcinus maenus.

These same rocky intertidal species were similarly affected along Cornish coasts in 1967 after exposure to a mixture of detergents and crude oil spilled from the Torrey Canyon (Smith, 1968; Nelson-Smith, 1968a). However, in contrast to Smith's account that oil alone had caused little harm to shore life, effects on rocky intertidal organisms were observed in an area where detergents were allegedly not used prior to sampling.

Mussels, *Mytilus edulis*, were not observed on the rocks at Roscoff. However, dense populations were found subsequently at Locquirec (EPA station 4). The mussels were oiled, yet they appeared unharmed at that time.

Intertidal Sand Cove at Roscoff

The sandy cove between Roscoff and the Perharidic peninsula is almost entirely exposed at low tide. Consequently, oil not only concentrated in thick layers high up on the beaches, but with receding spring tides was also dispersed throughout the cove. This spreading was observed as visible droplets of mousse at depth in the sediment and as occasional surface stains even in the middle of the cove. That the underlying sediment and ground water contamination had reached toxic levels was evident since some dead and moribund infaunal specimens were collected throughout the cove, particularly toward shore where the oiling was most concentrated. These species included the edible cockle, *Cardium edule*, the carpet shell, *Venerupis decussata*, and the polychaete, *Nereis diversicolor* (Fig. 5A-1). The epifaunal green crab, *Carcinus maenus*, was also found dead in large numbers.

Quantitative sampling of the three sand substations revealed a relatively diverse infaunal assemblage consisting of a rather large number of species (i.e., in comparison with the other stations, and in view of the rather small sample size and large sieve size used) (Table 5A-2). Structural variation between substations was observed, with the number of species and other structural indices (diversity, species richness, and evenness) increasing from substation 1 to substation 3. There are several possible explanations for this variation: (1) the greater availability of microhabitats toward substation 3 as a result of the increase in grain size, (2) an increase in environmental stability toward substation 3 (e.g., increase in depth of water at high tide and decrease in environmental fluctuations), and (3) the elimination of some species from substation 1 as a result of the greater concentration of oil on the beachface. The substation 3 sample consisted of 15 species and 73 individuals per 0.1 m^2, and was characterized by relatively high values for H'(3.34), D_G(7.51), and J'(0.85). The dominant organism was the polychaete, *Nereis diversicolor*, which was found at substation 1 at a density of 52 per 0.1 m^2. Abundant on the sediment surface were the shingled tubes of the polychaete, *Lanice conchilega*, (90/m^2) and the casts of the lugworm, *Arenicola marina*, (36/m^2); however these species were not well represented in the infaunal samples.

Table 5A-2. Species list and associated structural indices for the various research stations.

Species	Research Stations						
	Roscoff			Ile Grande	Corn ar Gazel		
	1-1	1-2	1-3	2	3-1	3-2	3-3
Polychaeta							
Nereis diversicolor	52	1	-	14	-	-	-
Scoloplos armiger	17	12	15	-	-	-	2
Polycirrus aurantiacus	1	1	1	-	-	-	-
Notomastus latericeus	2	5	20	-	-	-	-
Arenicola marina	-	1	-	1	-	-	1
Nephtys hombergii	-	1	1	-	3	-	-
Spio filicornis	-	1	5	-	1	-	1
Nicomache sp.	-	5	-	-	-	-	-
Aonides oxycephala	-	-	1	-	-	-	-
Nephtys sp.	-	-	1	-	-	-	-
Perinereis cultrifera	-	-	3	-	-	-	-
Lanice conchilega	-	-	3	-	-	-	-
Syllis sp.	-	-	1	-	-	-	-
Phyllodoce sp. A.	-	-	1	-	-	-	-
Phyllodoce sp. B.	-	-	-	-	-	-	1
Clymene sp.	-	-	13	-	-	-	-
Harmothoe lunulata	-	-	-	-	1	-	-
Glycera convoluta	-	-	-	-	-	-	2
Audouinia tentaculata	-	-	-	-	-	-	4
Amphipoda							
Haustorius arenarius	2	-	-	-	-	-	-
Phoxocephalopsis deceptionis	1	1	-	-	-	-	-
Decapoda							
Carcinus maenus	-	1	1	-	-	-	-
Cancer pagurus	-	-	-	-	-	1	1
Bivalvia							
Tellina tenuis	-	1	-	-	-	-	-
Loripes lucinalis	-	4	1	-	-	-	-
Loripes sp.	-	-	6	-	1	-	-
Gastropoda							
Littorina obtusata	-	-	-	-	1	1	-
S (no. species/0.1m^2	6	12	15	2	5	2	7
N (no. individuals/0.1m^2)	75	34	73	15	7	2	12
H'	1.30	2.90	3.34	0.35	2.13	1.00	2.58
D_G	2.66	7.18	7.51	0.85	4.71	3.33	5.56
J'	0.50	0.81	0.85	0.35	9.91	1.00	0.91

Since such large numbers of organisms were found still living within the sediments at the time of sampling on March 29, it appeared that up to this time many of the infaunal species had escaped initial impact. Perhaps the surrounding sediment provided a blanket of protection against immediate impact, whereas rocky intertidal organisms succumbed to the effects of direct physical contact with heavy oil slicks. These infaunal species are nonetheless considered at risk in view of several observations including the visible levels of sediment and ground water contamination throughout the study area, and the observed death of member organisms (e.g., cockles, clams, and polychaetes) in the immediate vicinity. Subsequent surveys of neighboring localities (e.g., at St. Michel-en-Grève four days later) revealed massive kills of infauna, particularly heart urchins (Echinocardium cordatum) and razor clams (Pharus legumen and Ensis siliqua). Dead urchins and razor clams were similarly reported along the Cornish coast after the Torrey Canyon spill (Smith, 1968). Also, impact of oil spills on soft-bottom intertidal communities has been reported elsewhere by Hampson and Sanders (1969), Thomas (1973), and Bender et al. (1974).

A striking observation was that of reproductively active polychaetes throughout the infaunal samples. Perinereis cultrifera was found in its heteronereid stage, and other polychaetes including Phyllodoce sp., Glycera convoluta, and Nephtys hombergii were carrying numerous ripe ova. It is possible that adult mortality at such a sexually productive period could have an effect on the recruitment of young, thus significantly altering the numerical distribution of species for some time to come. Larval forms are also known to be extremely sensitive to petroleum pollutants.

Salt Marsh at Ile Grande

Oil coverage of the marsh at Ile Grande was extensive, contaminating vegetation (Juncus sp., Spartina patens, and Salicornia sp.) and leaving most mud surfaces coated with several centimeters of mousse. Dead and moribund invertebrates were commonly found in large numbers on the oil-soaked mud flats, and included polychaetes (Nereis diversicolor and Arenicola marina), cockles (Cardium edule), and green crabs (Carcinus maenus) (Fig. 5A-2).

Quantitative sampling of the infauna was conducted on March 30 along a mud flat immediately adjacent to the main channel. Sampling was nearly impossible because of the nature of the soft sediments coupled with the extent of oiling. Therefore only one substation was sampled, and this became feasible only after large areas of surface oil were scraped away. Table 5A-2 reveals the extremely low diversity at this site, with only two species present, Nereis diversicolor and Arenicola marina. Although Nereis was the most abundant, neither was found alive in large numbers.

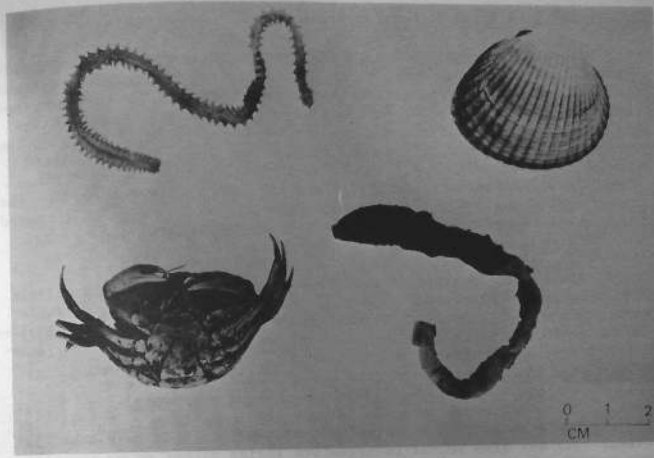


Figure 5A-2. Dead and moribund organisms at EPA Station 2, Ile Grande. Left to right: Top row--Nereis diversicolor and Cardium edule. Bottom row--Carcinus maenus and Arenicola marina.

It is not uncommon to find low species diversity in salt marshes. However, many characteristic marsh species large enough to be sampled in a 2.0 mm sieve (e.g., larger gammarid amphipods, capitellid and spionid polychaetes, and lamellibranch molluscs) were absent from the collection. It is believed that the observed absence of species is not only a result of the natural tendency for marshes to exhibit low numbers of species, but also a result of the demise of organisms as a result of the spill. Prior to this survey, Eric Gundlach at the same site reported thousands of moribund polychaetes attempting to escape their oily environment, only to end up on the surface of oil pools. Ecological damage to salt marsh communities has been reported previously as a result of the Chryssi P. Goulandris spill in Milford Haven, England (Nelson-Smith, 1968b); the Arrow spill in Chedabucto Bay, Canada (Thomas, 1973); and the West Falmouth spill in Massachusetts, U.S.A. (Michael et al., 1975).

Intertidal Sand Beach at Corn ar Gazel

Station 3 was situated on a high energy, ocean-exposed sandy beach, located approximately 500 m N.W. of the small town of Corn ar Gazel and 6 km S.E. of the wreck site. The beach was apparently once well coated with oil, since at the time of sampling on March 31 occasional stains and droplets were still visible both on the surface and at depth in the sediment. Also, grass growing on the sides of the steep dunes still showed traces of oil. For the most part, though, the waves and tides effectively removed the bulk of surface oil from the beachface. On the other hand, seaward the oil was still heavily concentrated and appeared as an oil-in-water emulsion throughout the water column. Nearby boulders located just offshore were still heavily oiled.

Toxicity was apparent. The jetsam line was littered with a large number of dead and moribund organisms, many of which revealed visible quantities of oil. Species included the edible crab, Cancer pagurus; an unidentified fish; the lugworm, Arenicola marina; an unidentified Holothuroidean (sea cucumber); the gastropods, Patella sp., Calliostoma zizyphinum, Gibbula cineraria, and G. umbilicalis; and the bivalves Dosinia exoleta, Venerupis pullastra, and Venus verrucosa (Fig. 5A-3). Some of these washed up from the neighboring rocks (e.g., Patella and Gibbula); others arrived from the soft-bottom intertidal and subtidal areas. Oil was also lethal to organisms living higher up on the shore. For example, Eric Gundlach observed on a similar beach 5 km west thousands of dead sand hoppers, Talitrus saltator, which normally live among the deposited jetsam. Many of these species were similarly affected after the Torrey Canyon spill (Smith, 1968).

Table 5A-2 reveals the results of the quantitative sampling of infauna. There were no apparent patterns in the distribution of species between substations and variation was most likely attributable to normal spatial patchiness. In general, values for the number of species, species diversity, and richness were between those observed at the two remaining stations. Values for J' for all three substations were particularly high, revealing an even distribution of the relatively few individuals among the species present. The presence of fewer species (particularly at substation 2), in comparison with the situation at Roscoff, was most likely a result of natural factors, such as a less stable physical environment (e.g., shifting sands and exposure to wave action). However, one should not rule out the possibility that some infaunal species were eliminated as a result of the oil, since visible oil levels were observed both in the water column and in the sediments. Also, many dead and moribund organisms were observed on the sediment surface in the immediate vicinity.

Here, as elsewhere, several species of polychaetes that were still alive were found in sexually productive states. Glycera convoluta, Nephtys hombergii, Audouinia tentaculata, and Arenicola marina were all carrying ova. One dead Arenicola that was examined also contained a large number of ova.

Figure 5A-3. Dead and moribund organisms at or near EPA Station 3, Corn ar Gazel. Left to right: top row--unidentified Holothuroidean, unidentified fish, and Arenicola marina. Middle row--Cancer pagurus, Venus verrucosa, Venerupis pullastra, and Dosinia exoleta. Bottom row--Gibbula cineraria, Gibbula umbilicalis, Talitrus saltator (above), Calliostoma zizyphinum (below) and Patella sp.

Summary

To assess the impact of the spill on onshore macrobenthos a reconnaissance survey was conducted with two objectives in mind: to observe and photograph obviously oiled, dead, or moribund organisms found on contaminated beaches; and to informally examine the spatial and numerical distribution of macrofaunal species considered at risk. Research stations included an intertidal sand cove with algalcoated rocky zones (Roscoff); a salt marsh (Ile Grande); and a high energy, ocean-exposed sand beach (Corn ar Gazel). All stations were heavily oiled. However, the marsh at Ile Grande was the most polluted. Removal of oil from the substrate surfaces as a result of the waves and currents was most effective at the higher energy stations, particularly at Corn ar Gazel.

Dead and moribund organisms were observed at all stations and included limpets (Patella vulgata), periwinkles (Littorina obtusata and L. littorea), topshells (Gibbula cineraria, G. umbilicalis, and Calliostoma zizyphinum), cockles (Cardium edule), clams (Venerupis decussata), polychaetes (Nereis diversicolor) and green crabs (Carcinus maenus) at Roscoff; polychaetes (Nereis diversicolor and Arenicola marina), cockles (Cardium edule) and green crabs (Carcinus maenus) at Ile Grande; and edible crabs (Cancer pagurus), fish (unidentified), sea cucumbers (unidentified), limpets (Patella sp.), top shells (Gibbula cineraria, G. umbilicalis, and Calliostoma zizyphinum) at Corn ar Gazel. Numerous dead amphipods (Talitrus saltator), sea urchins (Echinocardium cordatum), and razor clams (Ensis siliqua and Pharus legumen) were collected from neighboring sites.

Informal sampling of macroinfauna (>2.0 mm) revealed a relatively high diversity of species for the intertidal sand cove at Roscoff, an intermediate level for the sand beach at Corn ar Gazel, and an extremely low diversity for the marsh at Ile Grande. At Roscoff, 15 species and 73 individuals per 0.1 m^2 were collected from one substation, in comparison with only 2 species and 15 individuals per 0.1 m^2 at Ile Grande.

These infaunal assemblages are considered threatened because of the visible levels of sediment and ground water contamination and the observed kill of organisms in the immediate surroundings. Investigators should therefore make subsequent observations in these areas if possible to delineate future changes in the numerical and spatial distribution of species. It is anticipated that the preliminary species lists and observations presented here will be useful as "quasibaseline" information or guidelines for later comparison. However, if a long-term infaunal sampling program is initiated, a more sophisticated approach is recommended and should incorporate larger sample sizes and a smaller screen size for sieving (e.g., a 1 mm sieve in addition to the 2 mm sieve).

Several species of polychaetes were examined microscopically and were observed in sexually active states. The heteronereid stage of Perinereis cultrifera was found in one sample, and other polychaetes (Phyllodoce sp., Glycera convoluta, Nephtys hombergii, Andouinia tentaculata, and Arenicola marina) were carrying numerous ripe ova. Excessive adult mortality during such a sexually productive period could affect the future recruitment of species and thus accentuates the ecological significance of the initial impact.

References

Allen, J. A. (1962): Fauna of the Clyde Sea area. Mollusca. Scottish Marine Biol. Assoc., 88 p.

Allen, J. A. (1967): Fauna of the Clyde Sea area. Crustacea: Euphausiacea and Decapoda. Scottish Marine Biol. Assoc., 116 p.

Barnard, J. L. (1969): The families and genera of marine Gammaridean amphipods. Smithsonian Inst. Bull. 271, 535 p.

Barrett, J. and C. M. Yonge (1958): Collins pocket guide to the sea shore. Collins, London, 272 p.

Bender, M. E., J. L. Hyland, and T. K. Duncan (1974): Effects of an oil spill on benthic animals in the lower York River, Va. In Proceedings of Marine Pollution Monitoring (Petroleum) Symposium, Gaithersburg, Md., May 13-17, 1974. IOC-UNESCO, WMO, USDC-NBS, 257-260.

Bourdon, R. (1965): Inventaire de la faune marine de Roscoff. Decapodes-Stomatopodes. Editions de la Station Biologique de Roscoff, 45 p.

Bouvier, E. (1940): Faune de France, Vol. 37. Decapodes Marcheurs. Librarie de la Faculté des Sciences, Paris (Kraus Reprint, Nendeln-Liechtenstein, 1970), 404 p.

Chevereux, E. and L. Fage (1925): Faune de France, Vol. 9. Amphipodes. Libraire de la Faculté des Sciences, Paris (Kraus Reprint, Nendeln-Liechtenstein, 1970), 488 p.

Clark, R. B. (1960): Fauna of the Clyde Sea area: Polychaeta, with keys to the British genera. Scottish Marine Biol. Assoc., 71 p.

Cornet, R. and I. Marche-Marchad (1951): Inventaire de la faune marine de Roscoff. Mollusques. 5. Aux Travaux de la Station Biologique de Roscoff, 80 p.

Day, J. H. (1967): Polychaeta of Southern Africa. Part 1, Errantia; Part 2, Sedentaria. Brit. Mus. (Nat. Hist), 878 p.

Day, J. H. (1969): A guide to marine life on South African shores. A. Balkema Co., Cape Town, 300 p.

Eales, N. B. (1967): The littoral fauna of the British Isles; A handbook for collectors. Cambridge Univ. Press, 306 p.

Fauvel, P. (1923): Faune de France, Vol. 5. Polychetes Errantes. Libraire de la Faculté des Sciences, Paris (Kraus Reprint, Nendeln-Liechenstein, 1969), 488 p.

Fauvel, P. (1927): Faune de France, Vol. 16. Polychetes Sedentaires. P. Lechevalier, Paris, 494 p.

Gosner, K. I. (1971): Guide to identification of marine and estuarine invertebrates. Wiley-Interscience, N.Y., 693 p.

Hampson, G. R. and H. L. Sanders (1969): Local oil spill. Oceanus, 25:8-10.

Michael, A. D., C. R. Van Raalte, and L. S. Brown, (1975): Long-term effects of an oil spill at West Falmouth, Mass. In Proceedings of Conference on Prevention and Control of Oil Pollution, San Francisco, Calif. March 25-27, 1975, API, EPA, USCG, pp. 573-582.

Nelson-Smith, A. (1968a): Biological consequences of oil pollution and shore cleansing. In J. D. Carthy and D. R. Arthur (eds.) The biological effects of oil pollution on littoral communities, Fld. studies 2 (suppl.), 73-80.

Nelson-Smith, A. (1968b): The effects of oil pollution and emulsifier cleansing on marine life in south-west Britain. J. Appl. Ecol., 5:97-107.

Sars, G. O. (1890): An account of the crustacea of Norway, Vol. 1, Amphipoda (Text and Plates). Universitetsforlaget, Bergen and Oslo, 711 p.

Smith, J. E. (ed.), (1968): Torrey Canyon pollution and marine life. Cambridge Univ. Press, 196 p.

Tebble, N. (1966): British bivalve seashells. Brit. Mus. (Nat., Hist.), 213 p.

Thomas, M. L. H. (1973): Effects of Bunker C oil on intertidal and lagoonal biota in Chedabucto Bay, Nova Scotia. J. Fish. Res. Board, Can., 30:83-90.

Truchot, J., and A. Toulmond (1964): Inventaire de la fauna marine de Roscoff. Amphipodes-Cumaces. Supplement Aux Travaux de la Station Biologique de Roscoff, 42 p.

6. OIL SPILL CLEANUP ACTIVITIES

Roy W. Hann*, Jr., Les Rice*,
Marie-Claire Trujillo*, and Harry N. Young, Jr.*

6.1 Introduction

The oil spill from the supertanker Amoco Cadiz off the Brittany Coast of France overshadows by far any other oil spill into the marine environment. In terms of oil reaching the shore, it was on the order of four times the amount of the Torrey Canyon spill in the same general geographical area or the Metula spill in the Straits of Magellan. As a result, the spill and the subsequent activities to clean up the oil and mitigate damage provided a fascinating laboratory for those interested in institutional structure, planning, resource requirements, technology, and training to deal with disasters of this magnitude.

Those who wish either to evaluate the cleanup operations from the Amoco Cadiz or to prepare to deal with a similar problem elsewhere need to have a good grasp of the size of the problem. The oil, the resulting oil-water emulsion (mousse), and sand, seaweed, and detritus that became incorporated into or contaminated by the oil, were enormous in volume and weight. Fig. 6-1 shows the 220,000 metric tons of oil spilled,

WEIGHT AND VOLUME OF OIL	WEIGHT AND VOLUME OF MOUSSE GENERATED (based on 40% evaporation and loss to to water column
220,000 Metric Tons	488,371 Cubic Meters of Mousse
232,558 Cubic Meters of Oil (.86 S.G.)	488,371 Metric Tons of Mousse (SG=1.0)
1,613,000 Barrels (7.33 Barrels/Ton)	18,940,000 Cubic Feet of Mousse
67,760,000 U.S. Gallons	537,208 U.S. Tons (2,000 lb)
232,558,000 Liters	141,621,000 U.S. Gallons of Mousse

Figure 6.1. Relative weight and volumes of oil and mousse expressed in different units.

*Texas A&M University, College Station, TX 77840, participating under the support of the NOAA-USCG Spilled Oil Research Team

expressed in different weight and volume units. The volume of oil that will come ashore or could come ashore in a spill is a function of many parameters. A schematic diagram of these processes is shown as Fig. 6-2.

As will be discussed in the next section, the Amoco Cadiz oil on the water surface quickly became emulsified with approximately 2.5 parts of water by volume mixing with 1 part of oil. On the basis of this ratio, and assuming that 40 percent of the oil was lost to the atmosphere by evaporation or into the water column by natural dispersion or by going into solution, the volume of mousse that had to be dealt with ashore was calculated to be over 488,000 metric tons. The total is also expressed in Fig. 6-1 in different weight and volume units. This amount of mousse is capable of coating 359 miles of coastline with a layer of mousse 1 inch thick and 120 feet wide. The specific gravity of the oil-water mixture would range from 0.98 before the light ends evaporate to almost 1.028, the specific gravity of sea water after the light ends evaporate.

To provide a further measure of the volume of oil or mousse with which one must deal, it is worthwhile to relate it to the load capacity of the shore based equipment that must move the material. Fig. 6-3 shows the numbers of farm honeywagons, commercial vacuum trucks, dump trucks, tank trucks, and railroad tank cars necessary to move this amount of mousse. These numbers do not include the volume of seaweed, sand, and other detritus that are collected with the mousse and that in the later stages of the cleanup predominate in weight and volume, often

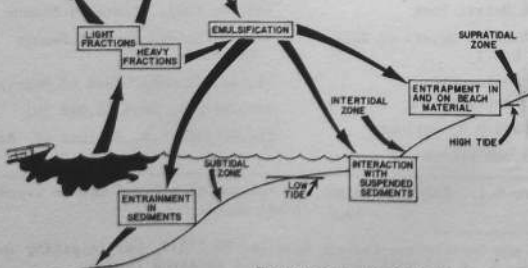
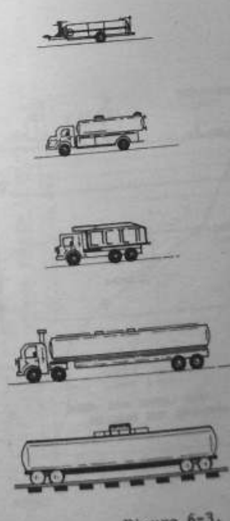


Figure 6-2. Mass balance components.

being equal to 20 times the amount of oil collected. The figures should help the reader to recognize the magnitude of the problem facing the French administrative system when the spill took place at an unforeseen time and place.

In this chapter, the authors discuss in detail the physical properties, behavior, and movement of the oil and its ultimate deposition on the beaches. The organizational structure established to deal with the spill and the strategy of control that appears to have been followed are presented and evaluated with regard to their utility in other spills. In addition the processes and unit operations used on the beaches are discussed. Estimates of the manpower and equipment used at different times throughout the spill are based on extensive reviews of newspaper



VOLUME OF LOAD	LOADS TO MOVE MOUSSE
750 gallons	188,830
1,800 gallons	78,678
252 cu.ft. 1,884 gallons	75,170
4,000 gallons	35,405
8,000 gallons	17,702

Figure 6-3. Equivalent truck and tank car loads necessary to remove potential volume of mousse from shore.

reports and daily pollution reports issued by the Department of Equipment. The final section discusses what has been learned from this experience.

6.2 Physical Properties, Behavior, and Movement of the Oil That Affected Control Operations

The general dimensions of the Amoco Cadiz and locations of the breaks in the hull are shown in Fig. 6-4. The oil lost from the Amoco Cadiz was a mixed cargo of Light Arabian Crude and Light Iranian Crude and the remaining Bunker C fuel of the ship.

Shortly after grounding at or near midnight on March 16, 1978, the ship broke in two near the bulkhead between the third and fourth (and last) row of tanks. In addition many of the other tanks were punctured or the bulkheads broached. Thus the early release of oil was a major one. The hull broke a second time approximately a week later near the foreward port of the number 2 row of tanks, resulting in another heavy release.

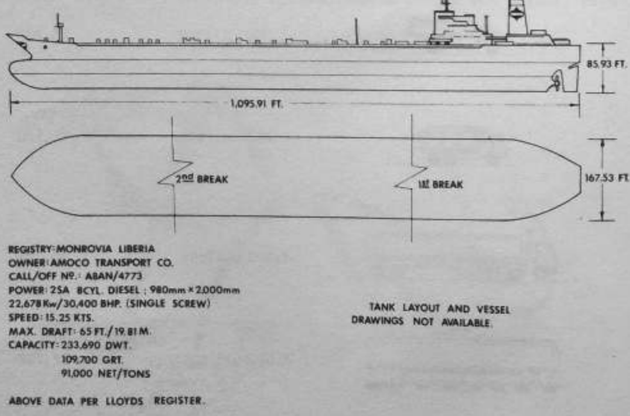


Figure 6-4. General layout and dimensions of Amoco Cadiz showing locations of breaks.

In the second week, the newly escaped oil recontaminated cleaned areas causing additional work, and negatively affected the morale of the cleanup workers ashore. To overcome this problem, the ship was bombed to release the remaining cargo. Fig. 6-5 is an estimate of the cumulative releases of oil from the ship compiled from newspaper reports and other sources.

During the first 11 days of the spill, during which it is estimated that 90 percent of the cargo was lost, the winds ranged from the west to the northwest at speeds of about 20 to 30 knots. The wind-driven transport vector was superimposed on an oscillating tidal component from the southwest to the northwest with an excursion of ~8 kilometers with neap tide to 15 kilometers with spring tides. This tended to spread the oil into a broad band to be carried toward shore.

The wind vector coupled with the deflection of the coastline caused the oil to spread along the coastline in substantial volume from approximately 10 kilometers south of the site of the grounding to approximately 200 kilometers to the east. The heaviest oiled areas were

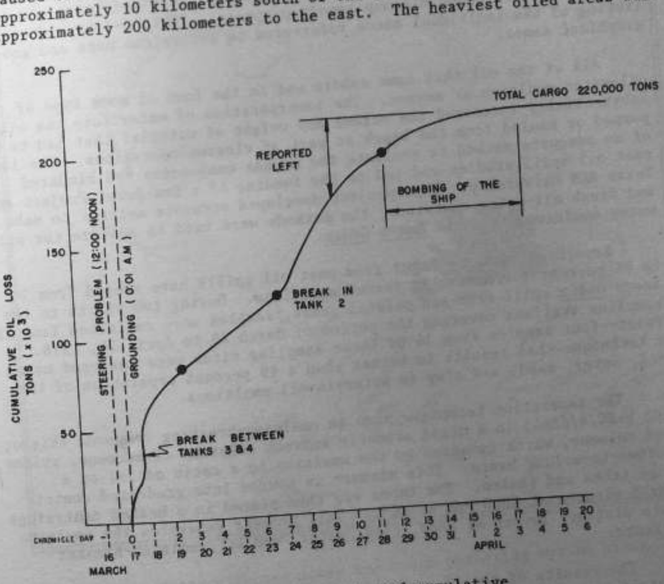


Figure 6-5. Estimated cumulative oil release from Amoco Cadiz spill.

the beaches, coves, and estuaries with openings to the west. Those that faced east and northeast were generally spared from substantial initial deposits of oil.

Northeast winds during the third and fourth weeks after the spill moved the oil southeast along some of the beaches and extended the impacted zone south from the spill site an additional 10 kilometers along the western Brittany coastline to Pointe de Saint Mathieu.

Major zones of the coastline that were affected are shown in Fig. 6-6, which also gives the numbering system used to identify the individual beach areas. On this map the coastal areas to the south and west of Pointe Scoune, north of Portsall, are given "W" designations, and those east and north of Pointe Scoune are given "E" designations. Not shown on the map are labeling systems for individual estuaries, such as AB-1 through AB-6 for l'Aber Benoit. This numbering system was used extensively during the trip of April 20 to May 1 for photo reference and for beach survey and beach cleanup report purposes. Table 6-1 is a detailed listing of the individual zones referenced to geological maps and geographical names.

All of the oil that came ashore was in the form of some type of oil-water emulsion or mousse. The incorporation of water into the oil substantially increased the volume and weight of material that had to be pumped or hauled from the beach as part of cleanup operations. The lack of an adequate method to evaluate the mousse components had hindered past oil spill studies and led to the funding of a Sea Grant Project at Texas A&M University, This project developed accurate methods to make and break oil-water emulsions; the methods were used to analyze the oil-water emulsions from the Amoco Cadiz.

Reports of water content from past oil spills have ranged from 20 to 85 percent for naturally formed emulsions. During two visits to the Amoco Cadiz spill site and coastal areas, samples were collected from 23 sampling stations covering the period of March 29 to April 24, 1978. Twenty-four samples from 16 of these sampling sites were analyzed using a technique that results in better than a 99 percent separation of the oil, water, sand, and clay in water-in-oil emulsions.

The separation technique uses an emulsion-breaking compound (Visco, 103 V-8074/6284) in a mixed aromatic solvent solution of benzene, xylene, and toluene, which is added to the emulsion in a ratio of 1:1 on a volume-to-volume basis. This mixture is poured into graduated centrifuge tubes and shaken. The tubes are then placed in a heated centrifuge for 5 minutes at 3000 rpm at 80°C. This process separates the emulsion into distinct layers of sand, clay, water, and oil/emulsion-breaker mixture.

The results of the 24 analyses are shown in Table 6-2. The water content ranged from a high of 91.25 percent to a low of 20.40 percent,

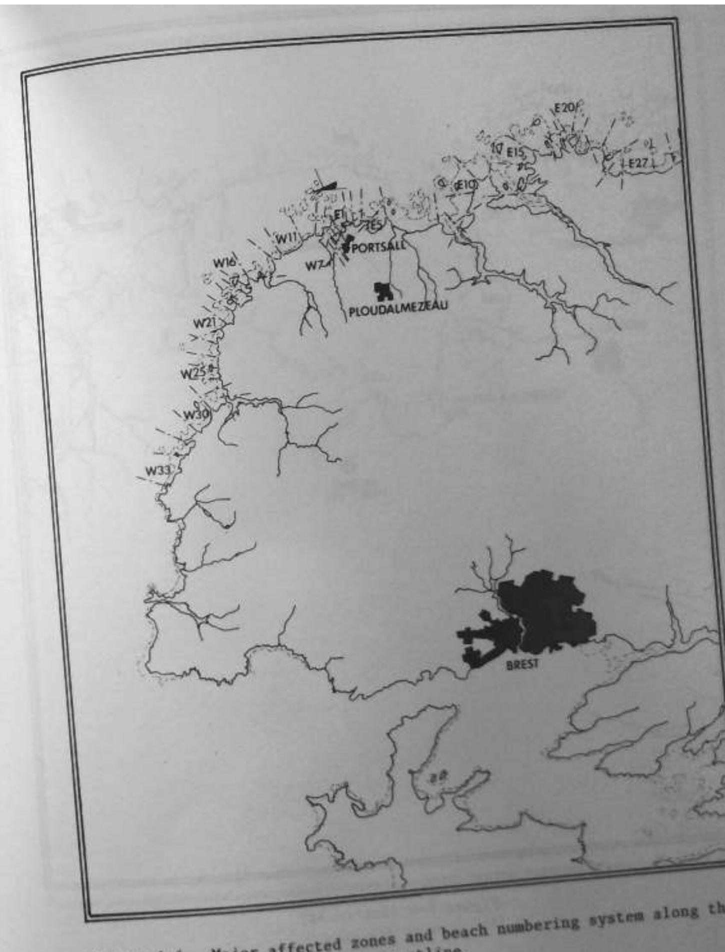


Figure 6-6. Major affected zones and beach numbering system along the Brittany coastline.

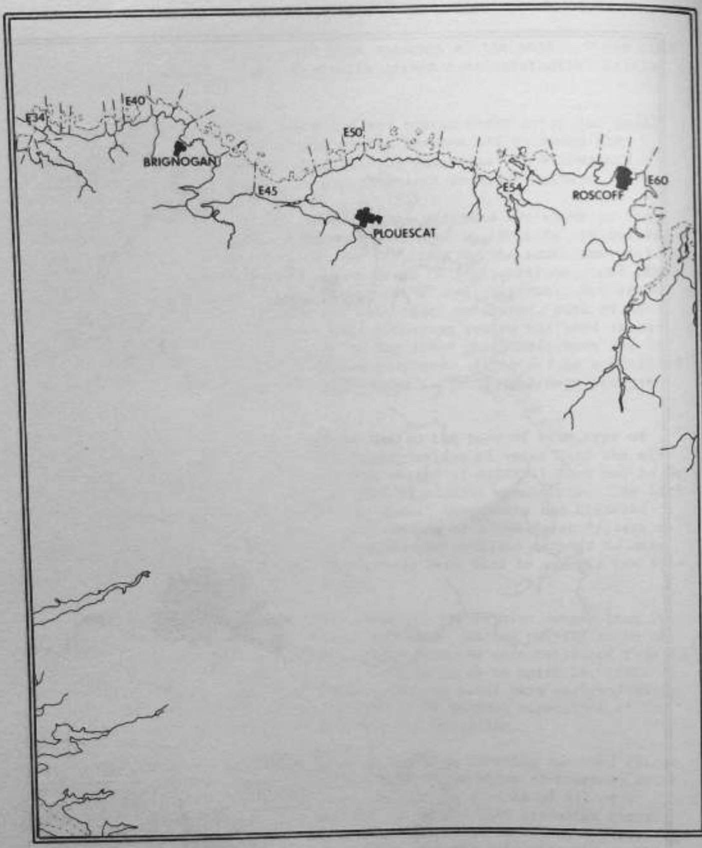


Figure 6-6 (continued).

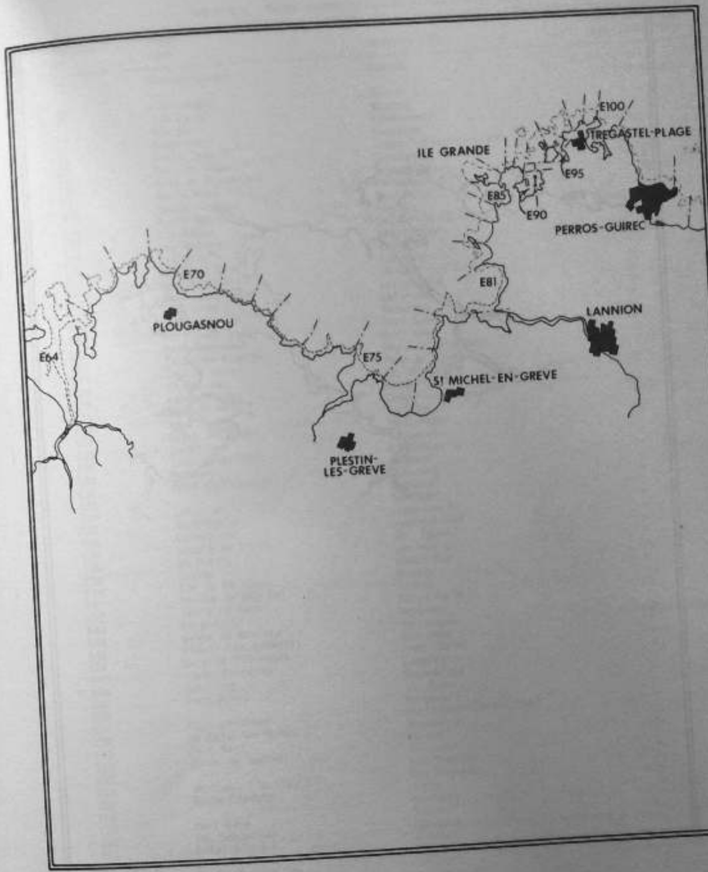


Figure 6-6 (continued).

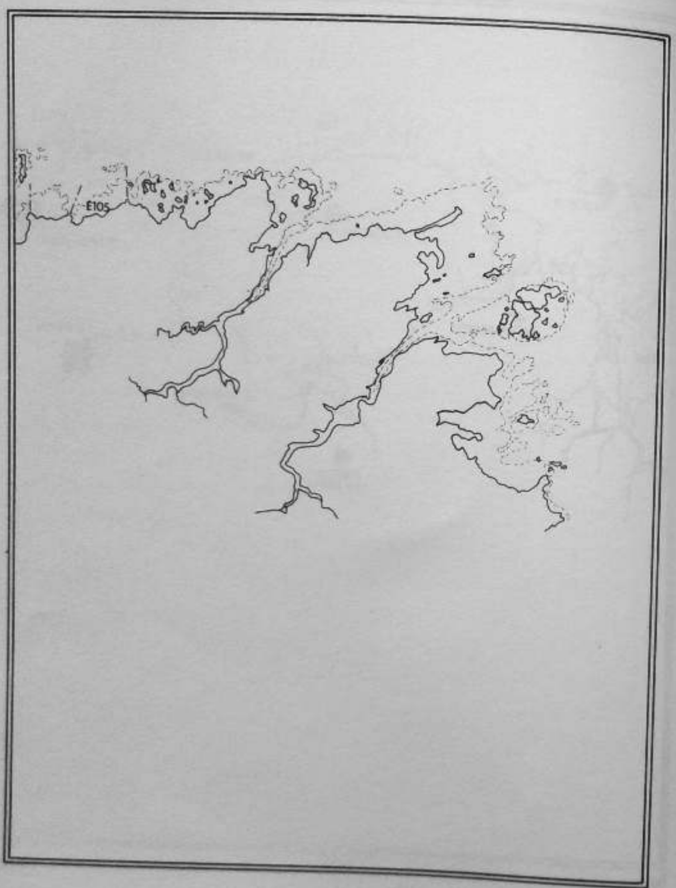


Figure 6-6 (continued).

Table 6-1. Beach numbering system of the French Coast

Section No.	Beach Name	Nearest City	Topographic Map Name (1/50,000)
E1	Pointe Scoune	Kerros	Plouarzel - Ile d'Ouessant
E2	Ile Longue	Kerros	"
E3	Ile Carn	Kerros	"
E4	Blockh	Dourlannoc	"
E5	Ruscaroc	Ruscaroc	Plabennec
E6	Roc'h Seac'h	Lampaul-Ploudalmézeau	"
E7	Corn ar Gazel	Kervigorn	"
E8	Anse de Brouennou	Brouennou	"
E9	Roc'h Avel	Kerennoc	"
E10	Carrec Adanet	Poulloc	"
E11	Roc'h Melen	Poulloc	Plouguerneau
E12	Ile Cézon	Quistilhe (Quistillie)	"
E13	Keridaouen	Keridaouen	"
E14	Ile Wrac'h	Kervezen	"
E15	Kervenny Braz	Kervenny	"
E16	Carrec du Bras	le Revn (le Run)	"
E17	Anse Lostrouc'h	Lostrouc'h	"
E18	Porz Grae I	Kelerdut	"
E19	Porz Grae II	Kelerdut	"
E20	Porz Guen I	Porz Guen	"
E21	Porz Guen	Porz Guen	"
E22	la Grève Blanche	Penn ar Stréjou	"
E23	Beg ar Spis	Penn ar Stréjou	"
E24	an Dol-Ven	St. Michel	"
E25	Kergoff East	Kergoff	"
E26	Kergoff West	Créac'h an Avel	"
E27	ar C'houlm	le Zorn	"
E28	Grève du Vougo	le Curnic	"
E29	Curnic	le Curnic	"
E30	Enez Croaz-Hent	le Curnic	"
E31	Nodéven	Nodéven	"
E32	Port de Trésseny	Guisseny	"
E33		Mentoull	"
E34	Loccarec	Mentoull	"
E35	Menbréac'h	Menbréac'h	"
E36	Carrec Hir	Boutrouille	"
E37	Louc'h an Dreff	St. Egarec	"
E38	ar Vorbic	Kerlouarn	"
E39	Carrec	Menez-Hom	"
E40	Ile de Kerlouan	Minioc	"
E41	Pointe de Beg Pol	Perros	"
E42	Terre du Pont	Terre du Pont	"
E43	Keravézan	Monbren	St.-Pol-de-Léon
E44	Grève de Goulven	Brignogan	"
E45	Kibell (ar Guibell)	Ker Emma	"
E46	Ae'r de Plouescat	Pont-Christ	"
E47	Corps de garde	Lannérien	"
E48	Enes Eog	Goas-bians	"
E49	Enez Névez	St. Eden	"
E50		Kergovara	"
E51	Clos-ar-Hélen	Kerfleien (Kerfissien)	"
E52	an Amied/an Holen	Kervaliou	"
E53	Port Neuf	Keraval	"
E54	Dunes de Santec	Kerabret	"
E55		Men Rognant	"
E56	le Stavl (le Staul)	Men Rognant	"
E57	Roche Blanche	Jugan	"
E58		Prateron	"
E59	Port Gare	Roscoff	"
E60	St. Sebastien	Kerezoun	"
E61	Créac'h André	Troméal	St. Pol-de-Léon 7-8
E62		Pempoul	Plestin les-Grèves
E63	Penzé Rivière Bay	Carantec	"
E64	Morlaix Bay	Locquénolé	"
E65		Kernéléhen	"
E66		St. Samson	"
E67	le Guerit	le Diben	"
E68	Pointe de Diben	le Diben	"
E69	Primel-Trégastel	Primel-Trégastel	

Table 6-1. (continued)

Section No.	Beach Name	Nearest City	Topographic Map Name (1/50,000)
E70	Ker Maria	Plougasnou	Plestin les-Grèves
E71	Kerdreîn	St. Jean-du-Doigt	"
E72	Beg an Fry	Kervourc'h	"
E73	les Charrues	Poul Rodou	"
E74	le Moulin de la Rive	le Moulin de la Rive	"
E75	Roches d'Argent	Locquirec	"
E76	Rocher Rouge	St. Efflam	"
E77	Grève de St. Michel	St. Michel-en-Grève	"
E78	an Treuzec	Trédrez	"
E79	Malabri	Kerguerven	Lannion
E80	Plage de Notigou	Locquémeau	"
E81	Plage de Porz Mabo	Beg-Leguer	"
E82	Plage de Tresmeur	Trébeurden	"
E83	Plage de Porz Terman	Crec'h Héry	"
E84	Goaz-Trez	Kerhellén	"
E85	Rulosquet	Dourlin	Perros-Guirec No. 5-6
E86	Ile à Canton	Dourlin	"
E87	Carr	Dourlin	"
E88	Pointe de Toul-ar-Staon	Dourlin	"
E89	le Corbeau	Porz Gélin	"
E90	Ile Mouton	Penvern	"
E91	Ile d'Erc'h	Kerénoc	"
E92	Ile Plate	Landrellec	"
E93	Ile Jaouen	Bringuiller	"
E94	Ile Tanguy	Bringuiller	"
E95	Kerlavos	Kerlavos	"
E96		Haren	"
E97	la Grève Blanche	la Grève Blanche	"
E98	Ile Ronde	la Grève Blanche	"
E99	Beg ar Vir	Ile Renote	"
E100	Ste. Anne	Ste. Anne	"
E101	Plage de Trestraou	Perros-Guirec	"
E102	Anse de Perros	St. Quay-Perros	"
E103	Feu de Nanthouar	Trélévern	Perros-Guirec
E104	Port l'Epine	Keriec	"
E105	Plage du Royau	Trévou-Tréguignec	"
E106	Anse de Pellinec	Penvénan	"
E107	Anse de Gouermel	Ralévy	"
E108	Baie d'Enfer	Kerbors	"
E109	Port la Chaîne	Pleubian	Tréguier
E110	Sillon de Talbert	Lanmodez	"
W1	Prat Léac'h-Kerros	Kerros	"
W2	"	Portsall	Plouarzel-Ile d'Ouessant
W3	Kerdeniel	Portsall	"
W4	Mon Repos	Portsall	"
W5	Portsall	Portsall	"
W6	Barr al Lann	Barr al Lann	"
W7	Barr al Lann	Barr al Lann	"
W8	Amer	Amer	"
W9	Beg ar Galéti	Trémazan	"
W10	Beg ar Manac'h	Trémazan	"
W11	St. Samson	St. Samson	"
W12	Pointe de Landunvez	Kerhoazoc	"
W13	Kerlaguen	Landunvez	"
W14	Penfoul	Landunvez	"
W15	St. Gonvel	Argenton	"
W16	St. Gonvel	Argenton	"
W17	St. Gonvel	Argenton	"
W18	Presqu'île du Vivier	Argenton	"
W19	Presqu'île St. Laurent	Porspoder	"
W20	Melgorn Bihan	Porspoder	"
W21	Melgorn Braz	Porspoder	"
W22	Radénoc	Porspoder	"
W23	Porspoder	Porspoder	"
W24	Poulloupry	Porspoder	"
W25	Mazou	Porspoder	"
W26	Prat ar Men	Porspoder	"
W27	Ile de Melon	Porspoder	"
W28	Mentiby	Lanildut	"

Table 6-2. Oil and water content of emulsions formed during the *Amoco Cadiz* oil spill

Beach No.	Date Collected	Clay %	Sand %	Water %	Oil %	Water: Oil Ratio	Oil: Water Ratio	% Water	% Oil
W11	20 Apr 78	0.45	7.30	91.25	8.00	11.41	.0876	91.94	8.06
W8	20 Apr 78	0.42	0.42	76.94	22.22	3.46	.2890	77.59	22.41
W5	29 Mar 78	0.74	0.59	57.52	41.15	1.40	.7143	58.30	41.70
E2	19 Apr 78	0.30	0.60	75.10	24.00	3.13	.3195	75.78	24.22
E2	19 Apr 78	0.44	0.57	68.70	30.29	2.27	.4405	69.40	30.60
E6	19 Apr 78	0.25	18.17	56.59	24.99	2.26	.4425	69.37	30.63
E6	29 Mar 78	0.75	3.75	75.50	20.00	3.78	.2646	79.60	20.40
E6	19 Apr 78	0.60	5.25	60.15	34.00	1.77	.5650	63.89	36.11
E6	19 Apr 78	0.42	1.76	65.19	32.63	2.00	.5000	66.64	33.36
AB4	23 Apr 78	64.50	3.00	22.50	10.00	2.25	.4444	69.23	30.77
AB4	29 Mar 78	1.76	1.91	75.71	20.62	3.67	.2725	78.59	21.41
E13	21 Apr 78	3.46	3.17	64.78	28.59	2.27	.4405	69.38	30.62
E15	21 Apr 78	1.16	1.58	72.30	24.96	2.90	.3448	74.34	25.66
E15	21 Apr 78	1.20	60.00	20.40	18.40	1.11	.9007	52.58	47.42
E59	29 Mar 78	1.60	0.92	63.28	34.20	1.85	.5405	64.92	35.08
E77	30 Mar 78	1.50	5.63	65.38	27.50	2.38	.4202	70.39	29.61

Table 6-2. (continued)

Beach No.	Date Collected	Clay %	Sand %	Water %	Oil %	Water: Oil Ratio	Oil:Water Ratio	% Water	% Oil
E77	23 Apr 78	0.00	65.25	21.75	13.00	1.67	.5988	62.59	37.41
E85	31 Mar 78	1.20	0.60	70.20	28.00	2.51	.3984	7.49	28.51
E85	23 Apr 78	0.90	0.90	50.20	48.00	1.05	.9524	51.12	48.88
E91	23 Apr 78	2.37	2.00	65.34	30.29	2.16	.4630	68.33	31.67
E96	30 Mar 78	0.60	2.25	73.15	24.00	3.05	.3279	75.30	24.70
E98	30 Mar 78	1.88	1.50	81.62	15.00	5.44	.1838	84.48	15.52
Trégastel	23 Apr 78	6.90	3.60	67.50	22.00	3.07	.3257	75.42	24.58
Penahr	29 Mar 78	1.88	5.25	70.90	19.97	3.65	.2740	78.50	21.50
					Avg.	2.94	.4379	70.78	29.16

Overall Oil/Water Ratio .41

Overall Water/Oil Ratio 2.43

The oil flowed freely and had a water content 20 percent less than an earlier sample.

The results of the analyses to date tend to indicate that emulsions of water-in-oil have a "life history" that can be traced from formation to final deposition or disappearance. Fig. 6-7 indicates possible pathways by which emulsions impact shorelines. The time scale, rates, and even probable pathways are missing because of the lack of knowledge about the fate of water-in-oil emulsions.

The behavior of the mousse on the beaches is of extreme importance to cleanup operations, particularly as the mousse moves back and forth with the tide and ultimately becomes stranded at or below the high tide line and as its specific gravity is increased through evaporation of light hydrocarbons and through the entrapment of sand. What starts out as a floating, pumpable, separable material, eventually becomes a relatively stable, heavy, nonpumpable material that must be either removed by hand or construction equipment, or left on the shore.

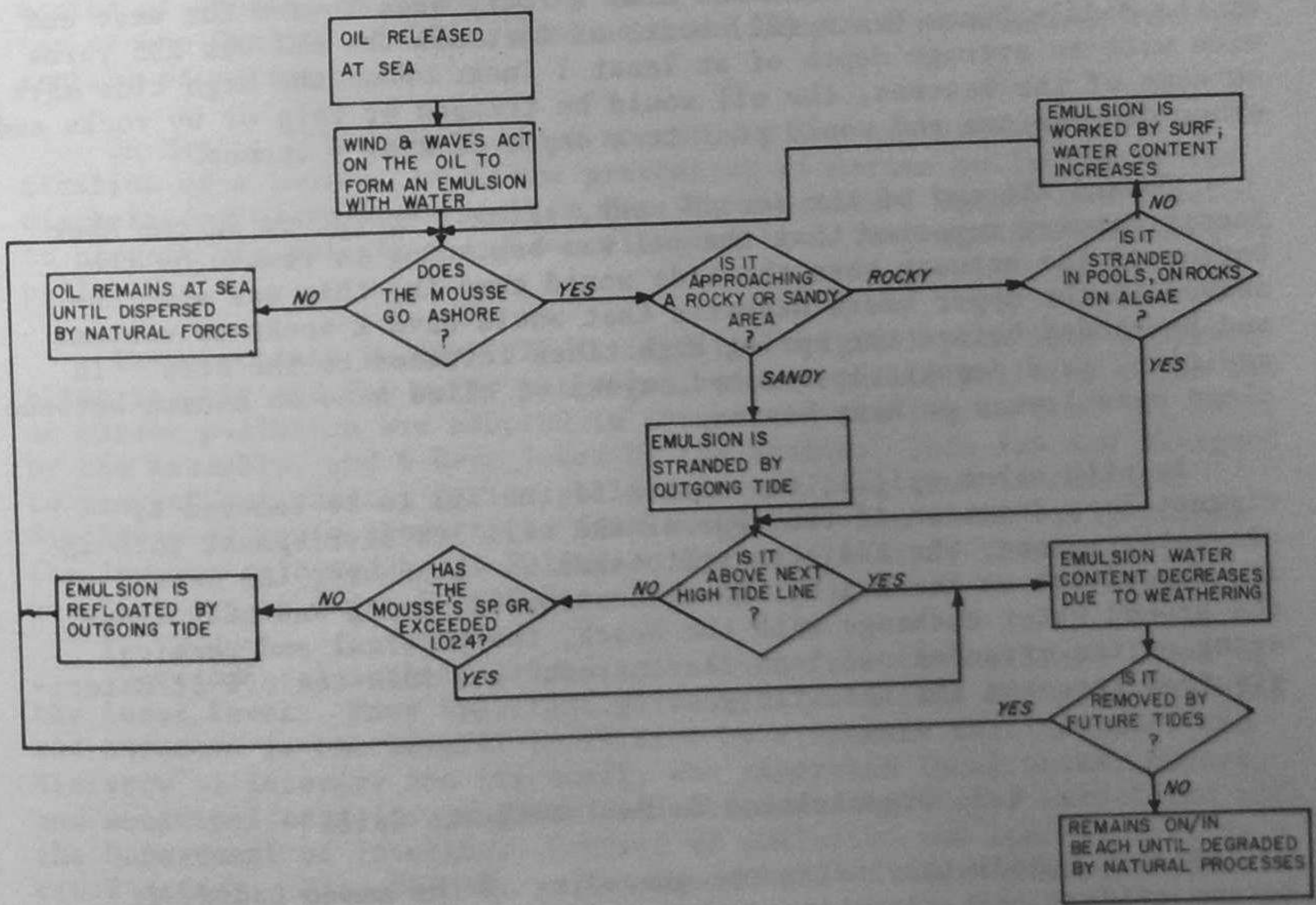


Figure 6-7. Possible pathways of oil spilled from <u>Amoco Cadiz</u>.

In the Portsall and Roscoff areas the mousse was quite thick on the water surface and amenable to direct removal. In most other areas, however, the oil was stranded on the beach with heaviest concentration in the high tide zone. Typically, the beaches would have a relatively stable oiled area at the top intertidal zone, which might be up to 50 meters wide. This oil would be stranded after the tides receded, and would either stay in place or slowly ooze down the beach front as a result of gravity.

Downslope in the middle beach area, the movement of the oil down the beachface was aided by ground water emerging from the sand. Quite often the oil would flow down the beach in rivulets on top of the flowing ground water. The oil that drained down the beach would pool in the lower intertidal zone or at the water's edge and then work its way up the beachface with the incoming tide.

For the most part, the mousse tended to bridge over the fine beach sands and did not appear to penetrate them. In rocky areas the mousse would lightly coat the face of the emerged rock and seaweed and would pool in the crevices around and between the rocks, sometimes to depths of 4 or 5 inches. North of Portsall Harbor (W3) the oiled beach at low tide was over 400 yards wide and near a rocky area toward the west end of the Middle Dunes Beach (E2) north of Portsall the oil was 235 yards wide with an average depth of at least 1 inch. Near the high tide mark on some of the beaches, the oil would be trapped by kelp or by rocks and other depressions and would pool to a depth of 2 to 4 inches.

Toward the end of the second week, skimmer operators in the Aber Benoit estuary reported that the oil was beginning to remain on the bottom of the estuary when the tide would come in; this was also observed in the upper beach deposits that would have 2 weeks to weather and be sanded before the spring high tides returned to the area. In addition, sand deposition created layers of oiled sand or mousse between clean sand layers on many beaches.

As with other spills, the nature of the oil to be removed by cleanup is a function of the type of the oil, its development into an oil-water mousse, the trajectory it takes to the shore, the method of its deposition on the beach, the succession of spring and neap tides, the ground water exchange with the beach, the physical and chemical aging of the stranded oil, and the introduction into the oil of materials that increase its specific gravity.

6.3 Organization To Deal With the Spill

Almost immediately after the grounding of the <u>Amoco Cadiz</u>, it became evident that cleaning up the spill would exceed the capacity of the ship owner (Amoco) or the cargo owner (Shell) using available company personnel or contract resources. It was also evident that cleanup

costs would exceed the resources available under TOVALOP or the Civil Liability Convention, whichever coverage was provided by the ship owner, or under CRYSTAL, the financial fund maintained by cargo owners. Consequently, the task of organizing and financing the cleanup operation fell to the government of France, which executed the plan POLMAR, corresponding roughly to the National Contingency Plan in the United States. A discussion of the development and organization of the plan within the local, regional, and central governmental structure of France will help explain why certain procedures were followed and how certain successes were achieved. It also explains how certain problems arose.

6.3.1 <u>Plan POLMAR</u>

In France, the President is advised by the Prime Minister and the Cabinet; the Cabinet guides policies of the nation, directs action of government, and is responsible for national defense.

On May 12, 1976, one of the two topics presented at the Cabinet meeting was a report of the status of the fight against pollution and the protection of the maritime frontier ("un bilan de la lutte contre la pollution et de la protection des facades maritimes"). After several months of debate, on November 3, 1976, Monsieur Vincent Ansquer, Minister of the Quality of Life, announced the adoption of measures for the control of marine pollution.

On May 5, 1977, the Cabinet accepted a law authorizing the ratification of a convention on the prevention of marine pollution by the discharge of waste products. On May 12, a national agency was created to prevent air pollution and was financed by a levy against combustible pollutants.

These actions in May 1977 divided the original plan into separate plans for air and for water pollution, with separate policies. The law on marine pollution was adopted in its second reading on June 18, 1977, by the Assembly, and 6 days later by the Senate. This law was designed to prevent and control marine pollution resulting from intentional discharge of waste products or from accidents. In these early stages the law was referred to as Pollution Marine. Shortly thereafter, it became known as "Plan POLMAR."

Governmental authority in France flows from the national level to the local level. Many important government decisions are made in Paris and enforced in the several localities by a network that includes the Ministry of Interior and its staff, who supervise local units, mayors, and municipal councils, and the prefects and subprefects associated with the Department of Interior. Control of pollution was conceived of as a civil matter. Plan POLMAR was the brainchild of the Ministry of the Quality of Life, but its execution was placed in the Direction of Equipment, which is comparable with U.S. state and local Departments of Public Works, insofar as its primary work is concerned. The Ministry of the Interior retained the enforcement powers. Since there was already a structure of local entities carrying out the policies of central government, it was reasonable to envision use of the same organizational structure to deal with a marine pollution incident such as a major oil spill.

At the time of the Amoco Cadiz wreck, Plan POLMAR had not been tested in a major incident. Immediately following the grounding of the Amoco Cadiz, Vice-Admiral Jacques Coulondres, maritime prefect of Brest, was placed in charge of Plan POLMAR. As time passed, it became increasingly evident that the fight against the oil spill would have two fronts: the sea and the coastline. Thus, Plan POLMAR was split into Plan POLMAR-Mer (sea activities) and Plan POLMAR-Terre (land activities). Vice-Admiral Coulondres retained control over the sea activities. The land activity was first placed under the responsibility of Monsieur Bourgin, but later passed to Monseiur Marc Bécam, former mayor of Quimper and secretary of the Ministry of the Interior at Paris. However, much of the strategy of the land activities and the details of operation were channeled through the Direction of Equipment offices in Finistère and Côtes-du-Nord, the two Departments constituting the affected coast.

On the local level, existing political structures were used for the land activities. The two affected Departments were each divided into four zones, each under the immediate responsibility of an engineer from the Direction of Equipment. It was soon learned, however, that the land activities required a great deal of organized manpower and the Army was called in. Establishing the unforeseen communication links needed between these organizations was a major, time-consuming task.

Plan POLMAR had no provision for use of volunteers in the event of a pollution disaster. This resulted in a tremendous problem for the administrators since the disaster occurred during the Easter break of the schools and universities, and many students wanted to volunteer. Eventually the problem was resolved by placing the administration of volunteers under the Ministry of Youth and Sports. A prospective volunteer first called the local office to demonstrate age, ability, and possession of necessary protective clothing and shelter. The volunteer was then assigned to a local area under the supervision of a foreman. This allowed for orderly use of the volunteer, protected the volunteer's personal safety and health, and discouraged vagabonds in search of free meals and lodging.

The response to the spill was a function of several factors: 1) an untested plan which continuously needed revising to adjust to unforeseen problems such as the two fronts and the volunteers; 2) the weather; 3) the existence of centralized control over local affairs and the execution of national policies through local units; and 4) the existence of certain communication channels and the lack of others.

and oil content ranged from a low of 8 percent to a high of 48 percent. There is no trend in the oil and water content with distance from the spill site.

In the four cases where mousse samples were collected at the same site (E6) in March and April, there was a significantly higher oil content in the April sample. This indicates that when the emulsion is stranded above current high tide lines and is subjected to sunlight, wind, and other forces, the water evaporates and leaves a material with a higher oil fraction.

The water-to-oil ratio evaluation indicates that the samples have an average of 2.43 parts water to 1 part oil. This ranges from 11.4 parts water to 1 part oil in fresh mousse at site W11 to almost 1:1 for weathered mousse at site E85. The average ratio of oil to water is 0.41.

Samples that gave the most extreme results indicate what happens to emulsions in different coastal and weather conditions. The sample from W11 was taken in a steep rocky coastal area from a large pool of light brown fresh mousse recently deposited in a natural rock-formed pool by an increasing series of high tides. This location receives very strong wave action, and any oil in the area would be highly emulsified and would have a very high water content. This was borne out by the 91 percent water content of the sample.

The two samples obtained from the Aber Benoit estuary (AB4) site indicate how the same site can yield different emulsions on different occasions. The sample taken on March 29 has a ratio of 3.67:1 of water to oil, which would be expected for a fairly fresh mousse. The sample taken on April 23, which showed a ratio of 2.25:1, has an unusually high clay value of 64.5 percent; this value is probably high because more than 25 percent of the clay volume is water. The oil had been exposed to 3 days of clear, sunny skies and warm temperatures, was very fluid, and had a dark black color. The wave action of the tide apparently mixed this mousse with the clay of the banks producing an emulsion having a high clay content.

The two samples obtained from E15 and also two from E6 showed that after an emulsion with a high water content has been exposed to the sun and wind, the mousse loses some of its water. When the incoming tide mixes this mousse with suspended sand, the mousse coats the sand, and consequently has a high sand content. This process was also observed in areas where cleanup operations mixed sand into the the emulsion (E6) or where pits were dug into the sand, filled with mousse, and covered again with sand (E77).

The final example of change in an oil/water emulsion is Ile Grande marsh (E85). At this site large quantities of oil were exposed to 4 days of clear sun, and the oil was 12°C (20°F) warmer than the water.

6.3.2 Organization in Finistère

The project team became more familiar with the organizational structure of the response in Finistère as a result of being located at and working with staff of COB/CNEXO, and through information provided by the Office of Direction of Equipment in Brest. The assistance provided by both organizations was outstanding.

Fig. 6-8 shows a simplified organizational chart of land activities in Finistère. The linkage with sea activities and the land activities in Côtes-du-Nord is also shown. Each of the sectors was under the direction of an engineer from Direction of Equipment, and also included a Lt. Colonel or Colonel who served as a liaison officer with the military troops working in the sector. Each sector was responsible for organizing daily activities in the field, requisitioning supplies, equipment and personnel, and providing the logistical support to the field activity. The Command Center in Ploudalmézeau coordinated sector activities, acquired and delivered logistical support, and arranged for ultimate disposal of the material collected in the field. Various supporting activities provided specialized technical advice or dealt with individual technical components of the logistical chain.

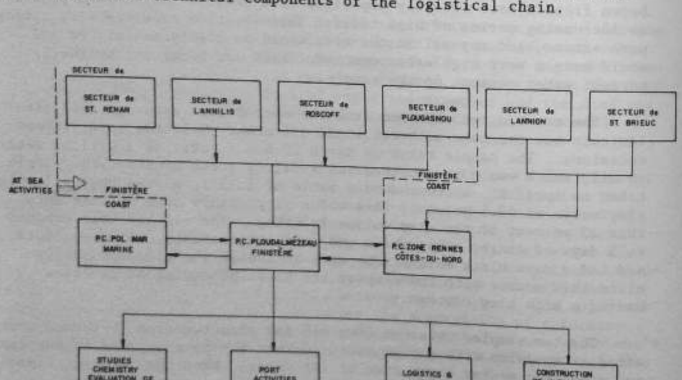


Figure 6-8. Approximate organization of the response effort.

Various units dealt with the physical aspects of oil removal. It appears that the initial response was from Civil Defense organizations, fire departments, contractors, and the French Navy. Follow-up response came from volunteers, Army units, public works departments, and additional contractors. In addition to the personnel involved with cleanup operations, the local scientific community--on both an organized and voluntary basis--was substantially involved in determing the short and long range behavior and impact of the spill.

6.4 Strategy of Control and Cleanup

From observations of this spill and from a general knowledge of the field, a strategy for spills of this magnitude emerges. The first step is to eliminate the oil or stop its discharge to the environment. In the Amoco Cadiz case, initial attempts were made to bring in pumping equipment to offload the cargo. However, the lead time required for equipment to arrive, the deterioration of the grounded ship, the adverse weather, and the difficulty of providing receiving tankage made elimination by cargo transfer impossible. Related to this step in the strategy was the decision to bomb the ship after some 90 percent of the cargo had been lost, so that the remaining oil would be spilled and would not continue as a pollution source after major cleanup had been achieved.

The second step in the strategy is to provide protection to the most environmentally sensitive areas. In this case, the mariculture facilities and the exposed estuaries that open to the west along the coast were considered the most important systems. Large numbers of booms were deployed in an attempt to protect these areas in the early days of the spill. Four days after the spill it was observed that the booms in l'Aber Benoit had been deployed correctly using angle theory, but other booms had failed either because they were damaged or because of entrainment. As the period of spring tide approached, all booms were ineffective because of the strong currents.

On the Lannion Peninsula, where there were several days of lead time before the oil reached the area, some resort communities bulldozed the top layer of sand from their beaches and stored it in piles at the high tide lines. The plan was to clean the oil from the newly exposed beach face and, after cleanup was completed, to cover the entire area with the clean sand that had been stockpiled.

A third phase is to prevent the oil from reaching shore. Prevention methods may include mechanical removal or the use of chemicals. In the case of the Amoco Cadiz, mechanical containment and removal were impossible because of local sea and weather conditions. Early attempts to use dispersant chemicals near shore were discontinued after the policy was established to refrain from using such chemicals in waters less than 50 meters deep. More than 35 boats ultimately were used to spread dispersants in deeper waters north and east of Roscoff and the Ile de Bréhat and south of Pte. de St. Mathieu.

The fourth phase of cleanup is the collection of floating oil from the surface of the water in locations where pumping and vacuum equipment can be used. Specific examples of this were in the Portsall and Roscoff areas.

The fifth phase is removal of stranded oil. In the Amoco Cadiz case, the priority that apparently was established was to remove stranded oil first from those areas with highest population or with high-use resort beaches. The first phase of the removal involved collection and pumping of the oil from the beach. This was accomplished by tactics such as the trenching and the digging of pits on the St. Michel-en-Grève beach, and the use of natural pockets and low points in other beaches. The removal of stranded oil also included washing down stone breakwaters and rip-rap areas that had been coated with water, and flushing the oil either into trenches or behind sand dikes.

Several marsh areas were affected in varying degrees. A large marsh in the Ile Grande area was almost entirely covered with oil 2 to 8 inches deep. The only course available to avoid the extended damage as seen in the Espora marshes impacted by the Metula spill in the Straits of Magellan was to remove the oil. Less oiled marshes observed near the Baie de Kernec and near Grève de Goulven were probably best left alone since removal of oiled vegetation would probably cause more harm than the moderate oiling.

A sixth phase of the strategy is to remove oil-contaminated materials. This includes removing oiled seaweed from rock, oiled sand from beaches, and oiled detritus of all sorts. The collected material is now low in oil content, but bulky and difficult to handle. Ultimate disposal of this material is a major problem.

A seventh phase of the strategy is to handle the collected mousse and detritus material for recovery or ultimate disposal.

6.5 Specific Cleanup Operations

A major activity of the Texas A&M team was to document the cleanup activities. During a series of visits to the cleanup site during 5 of the first 6 weeks following the spill, operations were observed visually and extensive photographs and 8-mm movies were taken. During the second project trip from April 15 through April 30, 1978, survey forms were filled out on the beaches at the time cleanup operations were observed. A copy of the form is shown as Fig. 6-9.

We believe that the most important part of the cleanup of this particular spill took place ashore where the oil was stranded against or on the beaches and rocky shoreline. Seven unit-process diagrams (Figs. 6-10 through 6-16) document cleanup operations on shore and serve as a

OBSERVER ____________

DATE/TIME ____________

AMOCO CADIZ

BEACH CLEANUP OPERATIONS SURVEY

1. Beach Number/Name/Descriptions ____________

2. Equipment utilized, size, type, amount, etc.
   - Boom ____________
   - Vac Trucks ____________
   - Tractors ____________
   - Bulldozers ____________
   - Honey Wagons ____________
   - Dump Trucks ____________
   - Tank Trucks ____________
   - Fire Engines ____________
   - Skimmers ____________
   - Other: ____________

3. Expendibles, Small Equipment, Sorbents, (shovels, rakes, garbage cans, etc.) - Types, How used, Est Quantities:

4. Personnel: (Approx. Number) ______; Laborers ______
   Equipment operators ______

5. Type of work force, i.e. contract, volunteer, military, civil defense - ______

6. Air temp ______ *WX. ______
   etc. ______ Water temp ______
   Wind velocity/direction (est) ______ Tide (in-out)/current ______
   Wave/swell systems ______ Physical consistence of oil ______
   Describe terrain, i.e. sandy beach, marsh, etc. ______

*Weather-sun, rain, partly cloudy - est. percent cloud cover - fog, etc

7. Samples collected(if any) - date time location no.

8. Describe the cleanup operation, sequence of events, usages of equipment, effectiveness, etc. ______

9. Still Photos- Roll# Frame #s. ______

10. Movies, Roll# est.footage. ______

Figure 6-9. Beach cleanup survey form.

guide to the color plates for this chapter. The processes of the Amoco Cadiz cleanup are discussed in sections 6.5.1. through 6.5.7. Also discussed are the other activities that contributed to the success or failure of the cleanup procedures.

6.5.1 Removal of Mousse From Water Surface Through Delivery to Interim Storage

A diagram of four unit processes used to collect mousse from the water surface is shown as Fig. 6-10. Much mousse was collected by vacuum trucks (A) at locations where ramps or causeways permitted direct access of the trucks to the oil during high tide periods. The tank trucks were able to pump the mousse directly from the surface because of the thickness of the mousse layer. Plate 6-1 shows vacuum trucks operating from a boat ramp in Portsall.

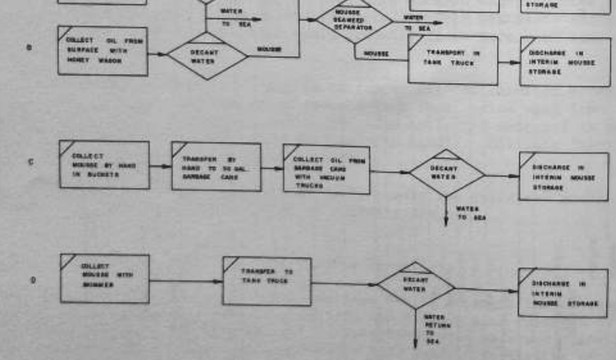


Figure 6-10. Unit process: Removal of mousse from water surface to interim storage.

A second method (B) involved the use of farm "honeywagons." Honeywagons are small vacuum trucks of 500 to 1000 gallon capacity, which are normally used to pump farm manure from cesspools and spread it on fields. Honeywagons drawn by tractors could work on the beach surface and follow the mousse as it moved with the tide along the beach. This equipment had the advantage of being able to work during a greater portion of the tidal cycle than could the vacuum trucks, which were restricted to hard surface roads; indeed, this equipment was the most important in the French cleanup effort. Plate 6-2 shows three honeywagons backed into the mousse on the beach to take on a load.

Both of these pumping operations were hindered since skimming devices were generally not available to separate the mousse and the water. As a result, large volumes of water were pumped into the tanks along with the mousse. Part of the mousse would separate out and water could then be removed from the tank by decanting; nonetheless, large volumes of water were often delivered to the interim storage areas. One report indicated that a tank truck brought 14 parts of water and 1 part of mousse to a storage area.

One of the problems encountered in pumping directly from the sea was the presence of large amounts of seaweed in the mousse. Open topped industrial dumpster units 8 feet wide by 20 feet long by 4 feet deep were brought to the scene to use as seaweed/mousse separators. The oiled seaweed mixture was pumped into baskets hanging over the dumpster units; the mousse was strained through the basket and the seaweed retained in the basket. The seaweed was then removed by hand and carried away to an interim bulk solid waste storage area. Several separators are shown at the top of the ramp in Plate 6-1.

Four Acme skimmers operated in the Portsall area. These skimmers discharged directly into vacuum or tank trucks, which then decanted excess water prior to delivery of the mousse to the interim mousse storage area. These compressed-air-driven skimmers from Tulsa, Oklahoma, are shown in Plate 6-4 and also in Plates 4-9 and 4-19.

Initial operations also included the simple bucket brigade whereby a large group of soldiers would scoop the mousse directly from the water surface in small buckets and pass the buckets to shore where the mousse was dumped into 30-gallon garbage cans. The mousse was then sucked into a vacuum truck for ultimate mousse/water separation and transportation to interim storage. This operation is shown in Plate 6-3.

6.5.2 Removal of Stranded Mousse from the Beach and Transportation to Interim Storage

During the period of increasingly high tide, mousse was resuspended and carried higher with each tidal cycle. When the spring tides began to recede, the mousse was deposited at each high tide and was not removed by the next tide interval. As a result, wide bands of mousse were stranded on the beach and a major activity became that of removing the mousse material.

The unit operations diagram for this activity is shown in Fig. 6-11. The first step was to concentrate the mousse where it could be picked up by mechanical equipment. This was accomplished by digging trenches or pits, or by using natural depressions or even squeegee boards to create a sufficient depth so that suction devices of the honeywagons could remove the mousse. Large numbers of soldiers pushed the mousse into these depressions and manned suction hoses.

The primary unit operation included concentration of the mousse, loading into the honeywagons, discharge into an oil/water separator to separate the seaweed from the mousse, and then transport by vacuum truck to the ultimate disposal area. Plate 6-5 shows a group of soldiers concentrating the mousse in a shallow pit and using vacuum hoses from two honeywagons to remove the mousse. This is also demonstrated in Plate 4-5. Plate 6-6 shows the use of a front-end loader with supplemental loading by hand to pick up the mousse, which was then loaded in the dump truck in the background to be carried away for disposal.

Plate 6-7 shows the collection of seaweed on a beach into piles both by hand and by mechanical means. The mousse drains away from the seaweed so that it can be collected in pits and trenches for removal.

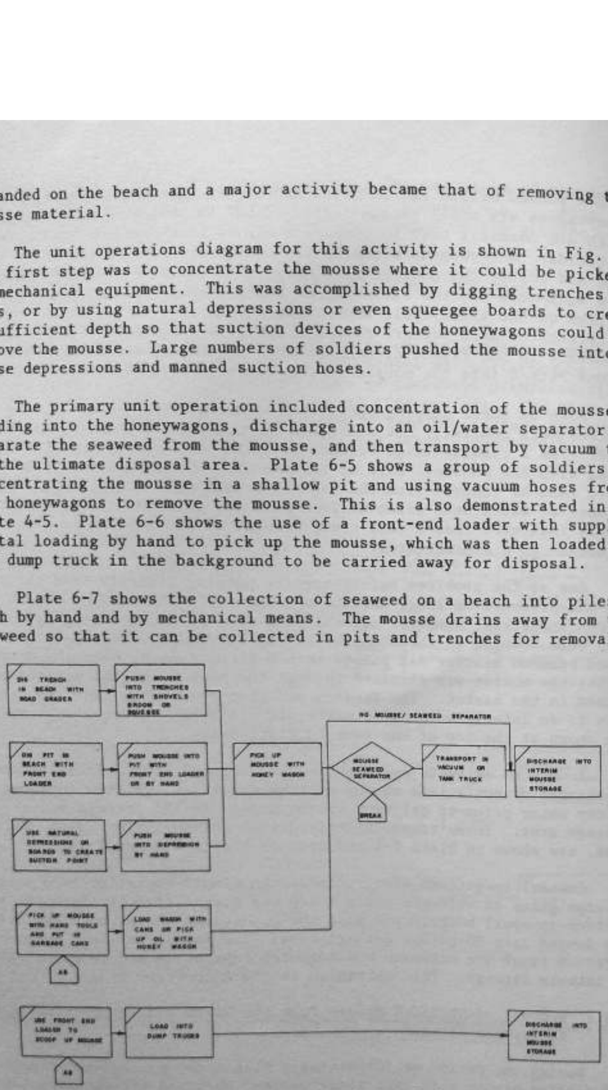


Figure 6-11. Unit process: Removal of stranded mousse from beach to interim storage.

Plate 4-8 shows a front-end loader with a load of seaweed and the farm trailer used to carry the seaweed off the beach.

Plate 6-8 shows a trench dug in the St. Michel-en-Grève beach to collect the mousse flowing down the beach so that it can be picked up by mechanical means.

Plate 6-9 shows a series of pits dug in the same beach to collect the mousse for removal by a honeywagon. The men are using homemade squeegee boards with long handles to push the mousse across the beach into the pits.

6.5.3 Removal of Mousse from Rocky Areas to Interim Storage

Large amounts of mousse were trapped in rocky areas, either by the pooling of the mousse in crevices and depressions or by the collection of mousse on algae. The algae on the rocks near the high tide line served almost as a natural oil absorbent. As the tide receded, the algae became dry as a result of wind and sun action. When the tide returned, bearing a mousse mixture on the surface, the algae became oil coated as the mousse came into contact with algae before it came into contact with the water. As a result, the algae would hold many times their weight in mousse. Plate 6-10 shows mousse absorbed in algae.

The removal of mousse from the rocky areas involved both the removal of the mousse trapped in the crevices and pools and the removal of the algal mass. Fig. 6-12 shows the unit processes for the removal of the pooled mousse and the mousse drained or squeegeed from the algae.

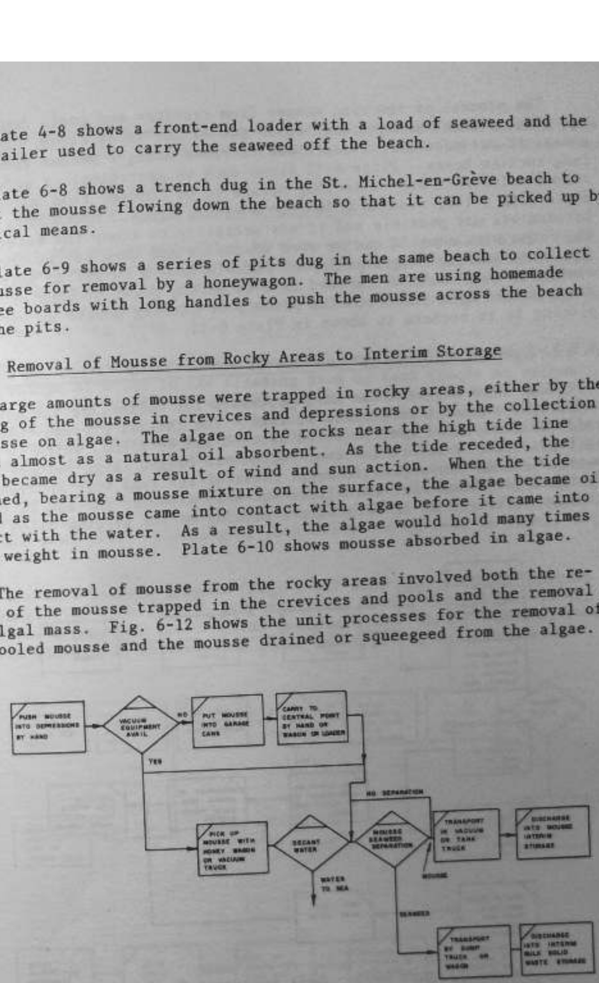


Figure 6-12. Unit process: Removal of mousse from rocky areas to interim storage.

The process of removing mousse from crevices and pools depended on how close mechanized equipment could get to the rocky areas. In a few cases, it was possible to reach the crevices using a vacuum truck and long suction hoses. Plate 6-11 shows such an operation: a group of seamen volunteers are collecting mousse to be removed from among the rocks with a long suction hose from a vacuum truck. Often this simple soluton was not possible and it was necessary to scoop the material from the rocks with a small can or even seashells and then to put the mousse into successively larger pails and finally into a 30-gallon garbage container that could be carried to a receiving point by hand or by farm wagon pulled by a tractor. The process of picking mousse up by hand and placing it in buckets is shown in Plate 6-12.

6.5.4 Removal of Oiled Sand, Seaweed, and Detritus to Interim Storage

Fig. 6-13 diagrams the unit processes for collecting and moving oiled bulk material to interim storage. The initial process covers the collection of oiled sand or oiled seaweed and detritus, which is placed in bags. Many soldiers and some volunteers bagged large volumes of oily materials into heavy plastic bags. Most of the bags were apparently designed for commercial fertilizer but were diverted for use in the cleanup. Plate 6-15 shows soldiers picking up and bagging oiled algae.

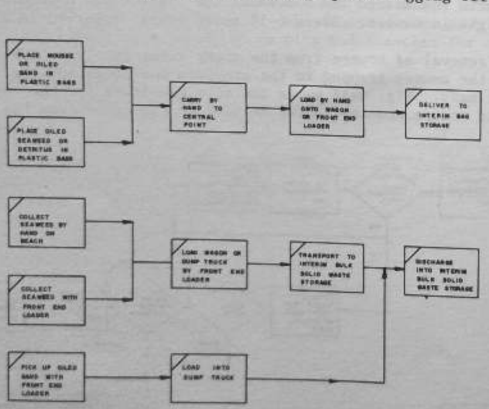


Figure 6-13. Unit process: Removal of oiled sand, seaweed, and detritus to interim storage.

Plate 4-5 portrays the operation of picking up bulk oiled seaweed from the beach. Similar operations included picking up oiled sand from some beaches.

6.5.5 Cleaning of Walls, Rock Faces, and Cobbles

Since the entire coastline in this region is a resort area, the cleaning of rocks, retaining walls, ramps, and boulders was necessary for both safety and aesthetic reasons. In the later stages of the cleanup considerable effort was given to this unit operation, which is diagrammed in Fig. 6-14.

The most complete cleaning operation consisted of the delivery of large volume of water to the cleaning area by tank trucks or vacuum trucks, the use of fire department pumping units to increase the pressure, and the use of fire for a high pressure stream with sufficient volume to flush the mousse into a collection area. Where the operation was done correctly, a containment area was established to collect the washed mousse and to pick it up for disposal. However, in many cases where the rocks or walls were washed the mousse was merely allowed to be trapped in sand, or if conditions were favorable, to be carried away with the next tide. Cleaning of rock walls can be seen in Plates 6-13 and 6-14.

The unit process diagram (Fig. 6-14) also describes the process of spraying oiled cobbles with dispersant and moving the cobbles to the lower beach zone for cleaning and redeposition. This procedure, shown also in Plate 6-30 is discussed under the topic of dispersants.

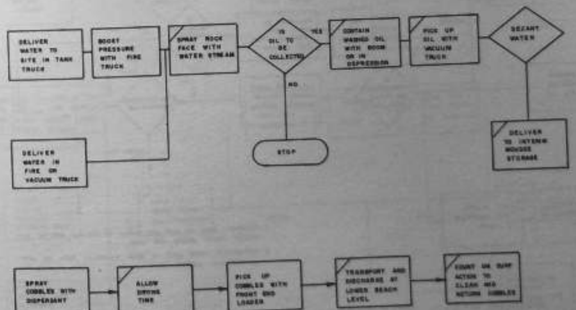


Figure 6-14. Unit process: Cleaning of walls, rockfaces, and cobbles.

6.5.6 Unit Processes for Cleaning the Ile Grande Marsh

The marsh areas at Ile Grande near the northern end of the Lannion Peninsula (E85 and E86) were heavily oiled, with mousse levels of 2 inches or more in grassy areas and levels ranging in depth from inches to feet in pools and channels. Experience gained in the Metula spill indicated that a marsh so heavily oiled would show no signs of life for years; therefore, oil removal, even at the price of vegetation removal and soil surface disruption, was warranted. Fig. 6-15 diagrams the operations observed and those expected to be used. The cleanup consists of the removal of the mousse and oiled vegetation where the mousse has covered the ground and the root stalk system. Where the soil is not covered, oiled grass should probably be left alone. Lightly oiled marshes such as those at Grève de Goulven and Baie de Kernec are probably best left alone.

Plate 6-16 shows a group of soldiers working with a small group of women volunteers in the Ile Grande marsh. The crane in the picture became bogged down while trying to create a channel to collect the mousse.

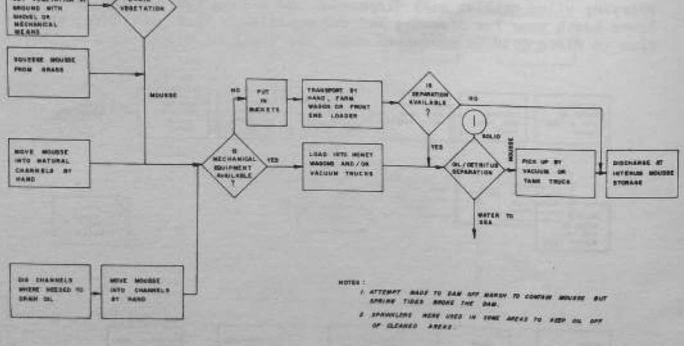


Figure 6-15. Unit process: Cleaning of Ile Grande marsh.

6.5.7 Movement of Mousse and Oiled Materials from Interim Storage to Final Disposal Sites

The volume estimates calculated in the initial section of this chapter indicated the huge amount of material that must be removed from the beach in such a spill. Since it is not desirable to tie up the limited equipment in transportation over long distances during the critical stages of the cleanup, a large interim storage much be created near the beach. Here mousse and solid materials are stored for periods from a few days to a few weeks, until sufficient equipment can be diverted from the mousse removal operations to carry the stored material to its final destination. A unit process diagram covering the processes from interim storage through disposal is shown in Fig. 6-16.

The primary interim storage devices used for mousse in the Amoco Cadiz spill were dug pits, which were either lined with plastic or left unlined. Plate 6-17 shows a typical group of interim storage pits located near Roscoff. Several honeywagons are unloading into one of the pits and vacuum and tank trucks are loading for transport. In the same region, a series of pits was used with screens placed between two pits (Plate 6-18) to serve as seaweed/mousse separators. Efficient loading requires the decanting of excess water from the tank of vacuum trucks as shown in Plate 6-19.

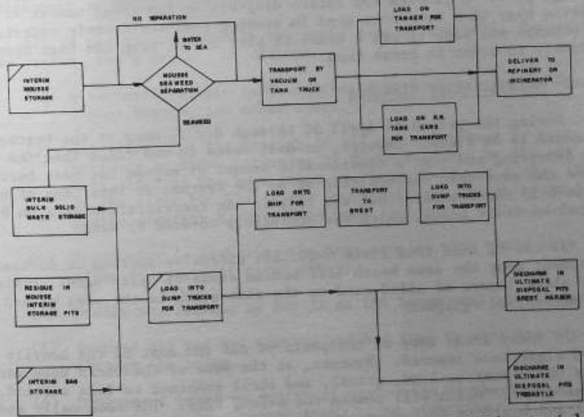


Figure 6-16. Unit process: Movement of mousse and oiled material from interim storage to disposal.

During the early stages of the spill, mousse from the Roscoff area was discharged into a small coastal tanker for transport to an oil refinery for processing. This tanker and the huge backlog of tank trucks waiting to be unloaded is shown in Plate 6-20. Later in the cleanup operation the mousse was transported by railroad tank cars to a refinery for either reprocessing or incineration.

In the later days of the spill, huge volumes of oiled sand, detritus, and seaweed were collected. This material also required interim bulk storage. In most cases bulk seaweed and sacked materials were stored on plastic sheets placed on flat ground with the edges built up to prevent any drainage. This material cannot be recycled for oil, nor does it have sufficient fuel value for burning. As a result, it posed a major problem. In the Department of Côtes-du-Nord, the material is being buried permanently near the town of Trégastel. One of the ultimate disposal pits is shown in Plate 6-21.

In the Department of Finistère several large storage pits have been constructed on the port property at Brest. Four pits ranging in size, from ½ to 1 acre have been constructed: first, pits with a depth of approximately 10 feet are dug and are lined with clay and then with a thick black plastic liner. Material is discharged into the pits pending future decisions to stabilize the material or use another form of permanent disposal. Plate 6-22 shows typical materials dumped into these storage pits. A problem for future disposal is the large number of plastic bags that have been used in storing semi-solid waste materials. An attempt was made to use a crane to pick up and drop the bags upon delivery in order to break them.

6.5.8 Results After Cleaning

During the period of April 20 through May 1, many of the beaches appeared to be clean. However, in most cases it was found that the view was deceiving and that a considerable amount of mousse had been buried under the sand that was building up on the beaches at this time of year. Plate 6-23 shows mousse that was left in the concentration pits on St. Michel-en-Grève beach, which was ultimately covered by sand.

It can be seen from Plate 6-24 that extensive working of mechanical equipment over the same beach left behind areas of oiled sand. Plate 6-25 shows layers of oiled sand on the same beach in the area worked by the mechanized equipment.

In rocky areas many of the pools of oil and most of the heavily oiled algae were removed. However, at the base of the rocks were many areas where mousse, sand, gravel, and shell combined to form a solid, "moussecrete," which will remain for a long time. The rock walls and ramps and boulders that were cleaned by water or with water detergent mixures were relatively clean.

6.5.9 Other Technologies

Booms

Many booms were used early in the spill to try and protect important areas, and later in the spill to aid in the recovery of mousse. The four types of booms used are shown as Fig. 6-17. The most frequently used boom was the French made Sycore II, an air-inflatable boom with a 1-meter skirt and the primary heavy-duty boom. It was reported that some 20 kilometers of this boom were available in France to be used for the spill; however, only 11 kilometers in good condition were available. This boom was too light and fragile for the heavy sea environment in which it was used, and the deep skirt created exceptionally large drag forces which damaged the boom fabric and end connectors.

The second type is the Acorn boom, which is filled with foam beads and has a shallower skirt. This boom appeared to be much more rugged, and under high wave conditions was observed to be following the wave profile exceptionally well. The boom appears to be more bulky to handle but much more effective in practice.

Two types of gamlen booms saw limited service. One is the "hi-sea" fence boom and the other is a small harbor boom with pockets for flotation. The latter boom generally appeared to be ineffective in the environment in which it was used.

All of the booms placed in the early days of the spill failed to some degree, for a variety of reasons:

(1) Structural failure as demonstrated by broken booms in Roscoff, l'Aber Wrac'h, and other areas.

(2) Entrainment or the passing of oil under the boom by high velocity as shown occurring in Plate 4-30 and by the oil on both sides of the boom shown in Plates 4-29 and 4-32. (Booms in the first two Plates are Sycores II and the third is the gamlen aluminum harbor fence boom.)

(3) Difficulty in anchoring the boom ends so they would work effectively at all tidal levels.

(4) Breaks and fouling by debris as the booms went unattended.

(5) Trapped oil was not removed and had time to work its way through the booms.

(6) Deployment based on equity of protection or shortage of boom was not made in a manner known to be effective.

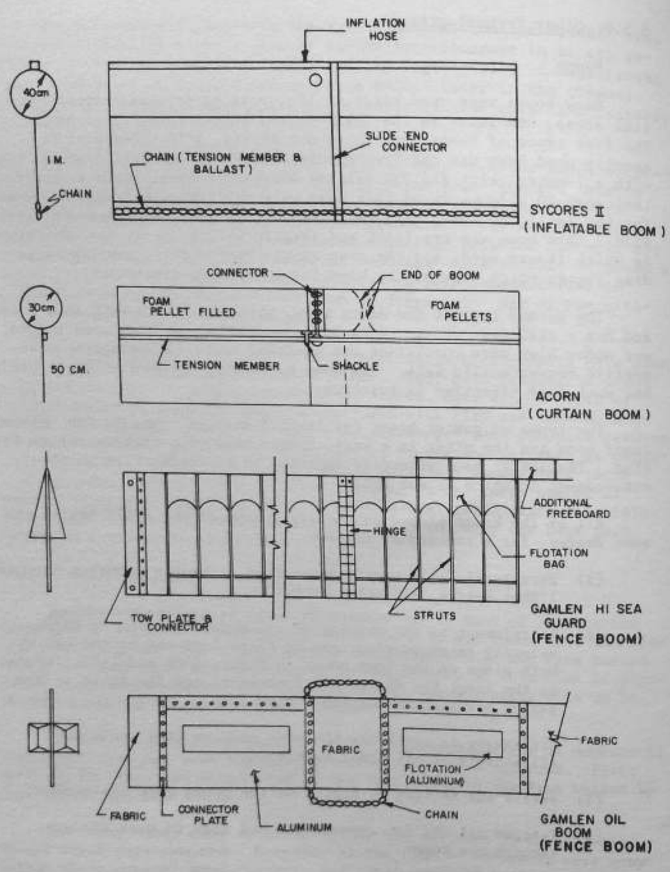


Figure 6-17. Four types of booms used during spill cleanup: (a) Sycores II; (b) Acorn; (c) Gamlen Hi-Sea Boom; and (d) Gamlen small fence boom.

Later in the spill, some of these problems were overcome with more boom, marine commandos to tend the boom, increased ability to remove trapped mousse, and more experienced supervision of placement. Removal personnel also learned to use booms on the beaches to collect oil for removal by vacuum trucks or honeywagons. Plate 6-26 shows effective placement of a boom in Aber Ildit.

Skimmers

Large skimmers generally proved to be ineffective because of the high sea state or lack of mobility. The Chamdis, a barge brought from Le Havre, had four large Cyclonet skimmers attached. It was able to operate only 2 hours over a 2-week period, but did achieve high rates of recoveries of about 40 tons per hour. Two French Navy ships, including the one shown in Plate 6-27, were equipped with Cyclonet units, but again were not able to recover much mousse because of high waves. A Vortex skimmer also had little success in the Roscoff area because of lack of mobility, high draft, and sea state.

Three small Oil Mop skimming units were used in the Aber Benoit and Aber Wrac'h areas and proved effective, although they could be used only during high tide periods. Thus total recovery was limited. More small skimmers of the Acme type used in Portsall would have been valuable.

Use of Dispersants

The policy governing the use of dispersants was discussed in section 6.4. Approximately 30 French and 6 British ships were utilized to spread dispersant. In the later stages of the spill a four-engine DC-4 aircraft was also used to spread dispersant. The primary dispersant used was the British Petroleum No. 1100 which is concentrated dispersant, but few data are available on amounts used or on effectivenss. The effectiveness of dispersants as a major control tool was limited by the broad distribution of oil along the coast, the patchiness of the oil in windrows, and the ability of a ship to cover only a limited area even during the better weather conditions. It is believed that considerably more oil was dispersed in the water column as a result of the high seas and the action of the seas with the rocky areas than was removed with dispersant.

Other Methods

After the Torrey Canyon spill the French Navy equipped itself to spread chalk on oil as a sinking agent. The method was used in the Amoco Cadiz spill even though numerous recommendations were made against it. Plate 6-28 shows a French Navy vessel discharging chalk on an oil slick southwest of Brest.

Other novel methods were used. For example, plaster was used at a site near the beach at Trégastal as an absorbent material in an attempt to remove the mousse from the coarse sand beach. The technique proved effective, but required tremendous amounts of labor to remove both the oiled materials and the chalk. (See Plate 6-29).

Spraying dispersant on rock and windrowing the rocks for cleaning and recycling by the surf were discussed earlier and are displayed in Plate 6-30.

The use of heavy equipment such as front-end loaders to move the mousse into collection areas on beaches is shown in Plate 6-31.

6.6. Resources Required For Cleanup

The authors have been concerned that many individuals thrust into oil spill cleanup activities misjudge the magnitude of the problem they face. This happens because most on-scene commanders or coordinators are chosen for some administrative or command talent and not as a result of an expertise in oil spill control. For this reason particular care has been taken in Section 6.1 to explain the magnitude of the spill in terms recognized by a person not familiar with oil transport terminology.

In this section, the authors have documented to the extent possible the level of effort in manpower, supplies, and equipment used to deal with the Amoco Cadiz spill and the amount of materials removed from the beaches. The information source used relative to land activities is good for the Finistère region, but almost non-existent for Côtes-du-Nord.

Logistical information on Navy activities is also sketchy. Although the number of vessels used is specified in the daily reports, information on manpower and use of supplies like dispersants is not provided. It is hoped that a detailed French report on this subject will be prepared and made available to the public.

6.6.1. Amount of Material Recovered

The daily pollution reports for Finistère listed amounts of recovered oil in three categories.

Material Pumped: This category included material pumped directly from the water surface into tank trucks or honeywagons.

Material Skimmed: This category included material skimmed from the surface of the beaches or rocky areas by men or equipment and moved off the beach by honeywagons, front-end loaders, or dump trucks.

Sacked Material: This category included mousse, oiled sand, oiled seaweed, and oiled detritus which was put in plastic bags and carried from the beach for disposal.

Figure 6-18 shows graphically the amount of oil which had been pumped from the water and the amount of material which had been removed from the surface of the beaches. It can be noted that the amount of oil removed by pumping from the surface and that the amount of oil removed from the beaches peaked in the last days of March and continued at a decreasing rate throughout April. The amount of material being collected in the last days of April up through the early days of May fell off considerably, which could be expected when less oil was floating on the surface and as the materials on the beaches became more contaminated.

Figure 6-19 shows the amounts of materials bagged by the men working on the beach. This includes the oiled sand, seaweed, and the other detritus that has been put in bags to be hauled away to the solid waste material storage areas. This operation began rather slowly because greater priority was put to the removal of the liquid oil, but peaked toward the end of April and the early days of May.

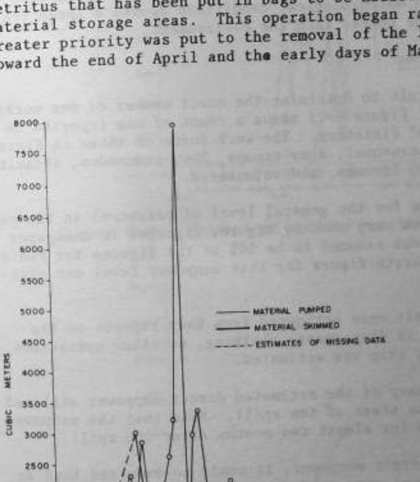


Figure 6-18. Volumes of spilled material pumped from water and removed from beach surfaces in Finistère.

Figure 6-20 shows the cumulative amount of materials removed from the beach. As of the first of May, the total amount of materials removed was approaching 100,000 cubic meters or approximately 100,000 metric tons. The accumulation of the total mount of material diminished as the oil became more diffuse and the material became more difficult to handle.

On the basis of the assumption that a cubic meter of mousse equals approximately a ton of mousse material and that the average oil/water ratio is 2.5:1, the material was roughly 30 percent oil. It can be estimated that 20,000 to 25,000 tons of oil have been removed from the coastline. If one compares these figures with those shown in Section 6.1, it can be observed that only about 15 to 20 percent of the mousse was removed. This indicates that the delay in removal coupled with the local oceanographic and meteorological conditions caused a large fraction of the mousse to be spread into the environment.

6.6.2 Manpower Resources

It has been difficult to determine the exact number of men working on cleanup activities. Figure 6-21 shows a count of men reported to be at work in the region of Finistère. The work force on shore in Finistère included public works personnel, Army troops, Navy commandos, security civil personnel, police, firemen, and volunteers.

Estimates were made for the general level of personnel in the region of Côtes-du-Nord based on very sketchy figures reported in newspaper articles. This figure was assumed to be 50% of the figures for Finistère. It is hoped that an accurate figure for this manpower level can ultimately be obtained.

Navy personnel levels were estimated from Navy reports of the number of ships engaged in dispersant, chalking, or other operations. An average of 35 men per ship was estimated.

Table 6-3 is a summary of the estimated direct manpower utilized at different times after the start of the spill. Note that the manpower effort continued to rise for almost two months after the spill.

In additon to the direct manpower, it could be expected that an additional 50% of personnel were needed as part of direct and indirect support roles.

During the middle of the spill cleanup, large numbers of volunteers were involved. However, problems of logistics and organization appear to have eliminated their effectiveness as a whole, although individual groups observed appeared to be highly effective. Few volunteers were able to stay for the duration of the recovery operation.

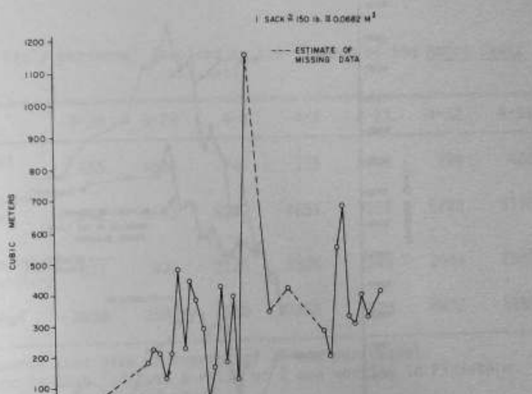


Figure 6-19. Volumes of spilled material bagged on the beach.

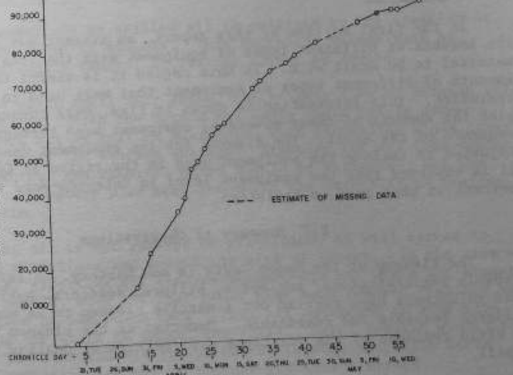


Figure 6-20. Total cumulative volume of spilled material removed from the beach.

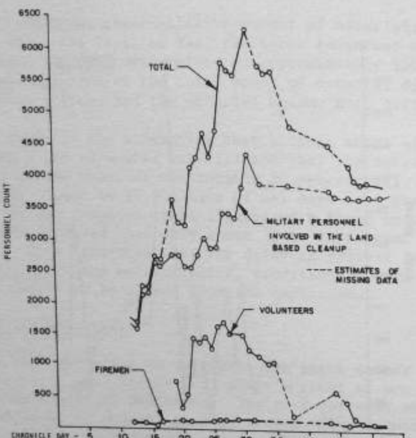


Figure 6-21. Numbers of personnel reported to be working on spill cleanup.

6.6.3 Equipment

In the first section of this report, an attempt was made to relate the amounts of different types of equipment with the total magnitude of material to be dealt with. In this regard it is useful to observe the amounts of different types of equipment that were used in the cleanup operation. This information is shown in Figs. 6-22 through 6-25 which plot the numbers of these pieces of equipment used throughout the time sequence of the spill. The figures for the equipment used must be adjusted to include the equipment used in the region of Côtes-du-Nord. It is expected that the equipment level in Côtes-du-Nord was 50 to 60 percent of that used in Finistère.

6.7 Summary of Observations

The cleanup of the Amoco Cadiz is now history. A large number of capable administrators, engineers, sailors, soldiers, public servants, and volunteers have carried out a massive cleanup to an end point considered feasible and reasonable. Memories of the cleanup will remain as a vivid reminder of the practical difficulties of dealing with a massive spill.

Table 6-3. Field personnel involved in the cleanup of the Amoco Cadiz oil spill

	3-28	3-29	4-8	4-9	4-11	4-12	4-18
Navy Personnel at Sea	455	1085	245	175	280	490	420
Military Personnel[1] in Finistère Province	1742	1663	4250	4651	4692	5288	5178
Military Personnel[2] in Côtes-du-Nord	871	832	2125	2326	2346	2644	2589
Total Personnel	3068	3580	6620	7252	7528	8422	8187

[1]Based on reports that give an average of 35 men per vessel.
[2]Based on reports that indicate a ratio of 2 men working in Finistère for one man working in Côtes-du-Nord.

Oil spill contingency planners should continuously evaluate their plans in light of the Amoco Cadiz experience. For this reason, it is appropriate to examine the characteristics of the spill and evaluate the response to it to see what lessons have been learned.

6.7.1 The Spill and Its Impact

(1) The magnitude of spilled oil is enlarged by the creation of water-in-oil emulsions or mousses. This increased volume must be considered in planning removal activities afloat or ashore.

(2) For a major spill near shore, the primary line of defense will be on the coastline. Both the Metula and Amoco Cadiz spills demonstrated that when oil is spilled nearshore, with prevailing winds toward shore, it will reach the beaches quickly. Stopping the oil from coming ashore by mechanical and chemical means should be attempted, but the backbone of a contingency plan must recognize the necessity of dealing with oil on shore.

(3) If the oil is not removed or stabilized, it will spread to uncontaminated coastlines and extend the area of impact. In the case of the Amoco Cadiz, effective oil removal onshore did not begin for almost a week. As a result, much oil that could have been removed remained on the water surface or the beach face. This oil continued to move with the winds along the shore to impact new areas. Later drastic windshifts from the west to the northeast in the third, fourth, and sixth weeks substantially redistributed oil to beaches previously missed.

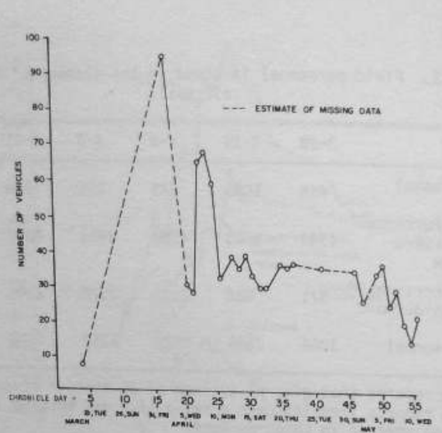


Figure 6-22. Numbers of tank trucks (camion citerne) used during spill cleanup.

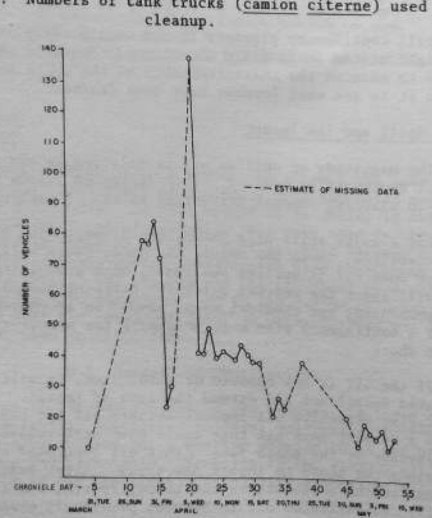


Figure 6-23. Numbers of vacuum trucks (camion d'assainissement) used during spill cleanup.

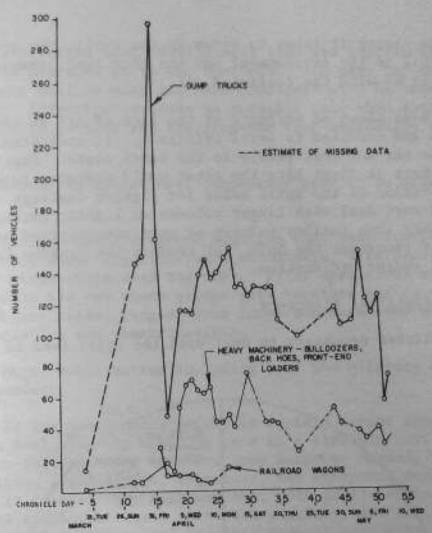


Figure 6-24. Numbers of dump trucks, heavy machinery, and railroad wagons used during spill cleanup.

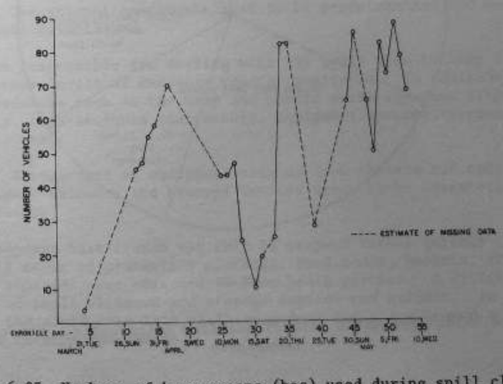


Figure 6-25 Numbers of honeywagons (bac) used during spill cleanup.

(4) The longer it takes to clean up the spill, the greater will be the loss of oil to the environment and the more sand, seaweed and detritus there will be with the collected oil.

Figure 6-26 shows an estimate of the fate of oil as reported in the French press and credited to local officials. It indicates substantial losses to the sea and most likely to the beach sands. Rapid removal of the mousse where it first hits the coast would minimize such losses. Greater dispersion of the spill makes for lighter coatings of more area. Then removal must deal with larger volumes of lightly contaminated material rather than smaller volumes of more concentrated material. This not only increases the bulk, but renders the residue less amenable to treatment and/or reclamation.

6.7.2 Organizational Structure

(1) Policies necessary to deal with the spill need to be predetermined.

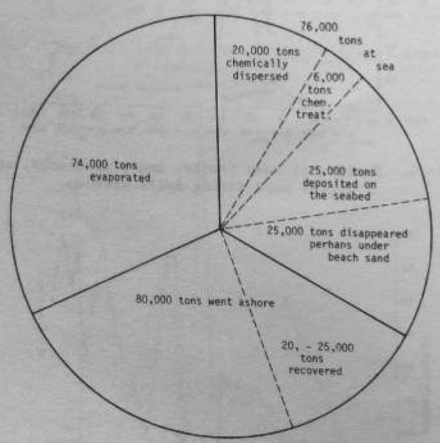


Figure 6-26. Estimated fate of oil from Amoco Cadiz. Source: local newspapers.

It was reported that considerable time was lost in the spill response while policies as to who does what, who pays for what (and how), which methods will be used and what chemicals will be used were being determined. Effective response is possible only when such issues have been decided in advance and the response team adequately informed of the decisions.

(2) Necessary operational components need to be organized and tested.

A large spill response requires that many functional groups such as public works organizations, volunteers, fire departments, soldiers, and contractors work together. Pilot operations need to be carried out to see how these groups work together and to see what operational problems arise, ranging from lunch schedules and union rules through logistics and communications.

(3) Major mobilization including both the military and public works is needed.

In the Amoco Cadiz spill, it rapidly became apparent that the attempt to deal with the spill on land as a strictly civil activity was destined to failure. Not only was Army manpower needed, but military communication, organization, logistics, and equipment were needed as well. It is increasingly apparent that both public works agencies and the Army or similar military units are necessary for the unique manpower, manpower training, and logistic support available from each.

6.7.3 Resources Necessary to Deal With a Spill

(1) Operational components need to be predetermined and mechanisms for response established.

Those responsible for dealing with the spill need to have resources for different levels of response readily available. In addition to the public resources such as the Army and public works agencies discussed previously, this includes contractors, equipment sources, cooperative agreements, etc.

(2) A reservoir of equipment ranging from shovels and containers through small skimmers and storage devices needs to be inventoried and made available.

It appears that France was able to respond rather quickly to supply the simple needs of protective clothing, hand tools, buckets, etc., but limiting storages were observed in some beach parties. A critical shortage of small skimmers and storage devices was evident. In many parts of the world, the lack of these modest tools may become a limiting factor in cleanup operations.

(3) Logistics need to be arranged to maximize the use of equipment during favorable tide and weather.

Often the matching of the tides, time of day, and normal workday resulted in extremely short working days for some unit operations. Lunch breaks were observed to shut down some operations during ideal time for removal of oil. Using shifts for the men on the beach and for machine operators could have resulted in much higher removal rates.

(4) Equipment and supplies to be used need to be determined beforehand. Examples were reported of fantastic prices charged where equipment was supplied without pre-negotiation of prices.

6.7.4 Specific Unit Operations

(1) Equipment compatible with the tide, current, and weather conditions must be chosen and tested in order to assure utility.

The failure of booms and skimmers to serve a meaningful role in the Amoco Cadiz cleanup is a reminder to choose methods of response compatible with the oceanographic and meteorological conditions of the area.

(2) Oil contained by booms, but not removed, will ultimately be lost to the environment.

This old adage of the field was borne out at the Amoco Cadiz spill. Booms that were effective during some tides or for part of the tidal cycle, would ultimately fail since the collected oil was not removed.

(3) Booms not tended are likely to fail.

Many of the initial boom deployments failed at the ends, by breaking or by being tripped by debris. Careful tending and mending in the early days of the spill could have lessened the damage in some areas.

6.7.5 Systems Approach to Unit Processes

(1) Large masses of simple equipment utilized by many people will be needed in the cleanup operation.

The magnitude of the problem in terms of volume of mousse, also the spreading into rocks, seaweed, and pockets of sand, indicates the amount of hand labor involved in removal of the material, particularly in the middle and later stages of the cleanup.

(2) A systems approach to examining unit processes and unit operations is necessary to eliminate waste and increase efficiency.

For efficiency and economy, it is necessary to match men with tools, supplies, and equipment in appropriate ratios, i.e., if 25 men can handle 1 honeywagon, having 100 men on the beach with only 1 wagon accomplishes nothing more. Similarly, if the same 25 men can load three honeywagons in series, then having only one wagon in service and having the men wait between loads is wasteful. Ratios of men to equipment need to be determined either before the spill or early enough in the spill to be adjusted.

(3) Levels of resource requirements for spills of different sizes need to be determined and published. The results of the Amoco Cadiz and other spills need to be analyzed to determine guidelines for the level of resources needed to handle spills of different sizes. This will help the on-scene coordinators immediately to assess the size of the response effort that will be needed.

6.7.6 Effective Contingency Planning and Training

(1) Overall contingency planning is necessary.

An effective contingency plan will contain many of the elements mentioned in this report. The plan must be a working entity, not merely a book on the shelf.

(2) Training is needed both before and during the spill.

It is essential to train administrators, engineers, and team leaders in oil spill control. In a spill as large as that of the Amoco Cadiz there is also a need for pretraining the manpower to be sent to the field. On-scene videotape methods may prove particularly valuable.

(3) All aspects of the plan must be tested periodically for readiness.

The major drawback of the French response was that the incidents of the Bohleme and the Olympic Bravery had not resulted in a full scale test of the POLMAR plan. The problems with the organizational components of the plan were the most important. However, all aspects of a contingency plan need appropriate testing.

APPENDIX A

Chronology of Events
March 16-April 20, 1978

The following is a chronology of events surrounding the Amoco Cadiz incident and activities of the U.S. scientific team:

March 16 — The Amoco Cadiz, carrying a cargo of 216,000 tons of light mideastern crude oil and 4,000 tons of Bunker fuel oil runs aground near midnight on a rock outcropping, 1.5 nmi from Portsall on the northwest coast of France. Three of 13 loaded tanks are emptied on grounding. Seas at the time of grounding are rough with 22- to 28-kn winds from WSW.

March 17 — Crew evacuated by helicopter at 0530. Vessel breaks forward of the wheelhouse at the level of the no. 4 tanks at 0600. Weather continues poor with strong W to SW winds.

March 19 — Vessel continues to leak. Shell Oil in charge of cleanup. Pumps being shipped from Detroit.

Six NOAA and NOAA-contract scientists arrive on-scene, contact CNEXO officials, and visit Portsall area. Weather foggy with 12- to 20-kn winds from WNW/NW.

March 20 — Vessel continues to leak with stern canted toward the east. Weather improves with good visibility in afternoon, 6- to 8-kn winds from the west. 50 tons of dispersant reportly used to date.

U.S. field party conducts observations at Portsall.

March 21 — Vessel continues to leak in 4- to 6-ft seas. Wind 20 kn from W/SW.

First U.S. fixed wing overflight reveals contamination extending from 10 km west to 80 km east of wreck site.

March 22 — Five tanks reported empty or leaking. Eight pumps on-scene with a total capacity of 1500 m^3. Nine French Navy ships are now on-scene with 100 tons of BP 1100 WD dispersant; five English ships standing by. Beach cleanup operations involving 310 individuals limited to pumping and recovering dense concentrations of oil. Shoreline contamination in varying degrees extends 145 km from Pte. de St. Mathieu to Bay of Lannion. Winds 5 to 15 kn from SW.

U.S. team conducts helicopter overflights in connection with shore-based beach and estuarine observations near Portsall.

March 23 — Vessel stern remains connected to bow. However all tanks appear leaking with 30,000-70,000 tons of cargo estimated to remain on-board. 20- to 30-kn winds gusting to 60 kn from WNW/NW, turbulent seas. 57 tons of dispersant used at sea to date.

U.S. team maps coastline and conducts five transects by helicopter from Portsall to Roscoff, obtains oil sample from near vessel. Ground surveys continue near Les Dunes beach.

March 24 — Vessel stern is shifted to west; new breaks are apparent. Winds 20 to 30 kn gusting to 45 kn. Sea conditions continue turbulent. Shoreline contaminated along 210 km from Pte. de St. Mathieu to Ile de Bréhat. Ten navy vessels and 3 U.K. tugs treating the spill with dispersant, with some additional support from helicopters. 450 individuals involved in beach cleanup.

U.S. team conducts helicopter and fixed-wing aircraft surveys of impact area, coordinated with beach surveys. Subsurface chemical sampling using a towed fluorometer is conducted in the Aber Wrac'h estuary, extending 6 km offshore.

March 25 — Vessel continues to leak in poor weather.

U.S. team continues transects by helicopter, beach survey, and subsurface chemical sampling in l'Aber Wrac'h.

March 26 — Close observation of vessel indicates extensive leaking from pipes at about 1 ton per minute. French Navy has opened hatches and valves on #1 tank. Winds 18 to 20 kn from the west.

U.S. team obtains oil sample 30 m from vessel by helicopter and maps beach area by fixed-wing aircraft. Beach surveys continue near l'Aber Wrac'h.

March 27 — Poor visibility prevents all aircraft operations. Winds 18 to 20 kn gusting to 35 kn from west.

U.S. team conducts beach surveys and subsurface chemical sampling in and near l'Aber Wrac'h.

March 28 — Ship broken in two with stern offset, bow inclined sharply from point of break. 10,000 to 50,000 tons of cargo estimated to remain on-board. Authorization to blow up tanker is obtained from owners and underwriters. Winds 30-40 kn from SW. Sporadic use of dispersants continuing from 6 English and 20 French ships. 1,420 people now involved in beach cleanup operations.

U.S. team conducts helicopter transects to 35 km off coast, encountering large patches of oil moving offshore. Shoreline region is filmed. Beach surveys continue.

March 29 — Depth charges used to rupture hull. Winds 15 kn from the SW. Beaches appear cleaner; however sheen and large patches of mousse are observed to 60 km offshore.

U.S. team conducts helicopter transects, fixed-wing overflights, and beach surveys.

March 30 — Depth charges again used to rupture hull. Vessel now broken in 3 sections; bow is elevated to 45°. Sky clear, winds light from SW. Less than 20,000 tons estimated to remain on board.

U.S. team conducts reconnaissance by fixed-wing aircraft and beach surveys. Offshore chemical sampling initiated aboard the French research vessel Le Suroit.

March 31 — Good weather, not much wind. U.S. team occupies 18 beach stations. Substantial kill of cockles and limpets observed near Roscoff and Portsall.

April 1 — Weather remains good. U.S. biologists visit lobster pound at Roscoff and find it must be rebuilt before use. Beach survey team continues second survey of standard beach stations.

April 2 — Good weather, light wind. U.S. team visits St. Michel-en-Grève to observe massive kill of heart urchins and razor clams.

April 3 — U.S. scientists meet with CNEXO and UBO scientists to review research efforts to date. Cleanup forces estimate 5000 tons of oil have been cleared from beaches.

April 4 — Vessel Le Suroit returns to port. U.S. biologists visit oyster culture dealer on l'Aber Benoit, bird hospital in Brest, and alginate factory.

April 5 U.S. scientists visit University of West Brittany.

April 6 Winds continue from the northeast for fourth day, although only a few areas in the far west appear to have been further contaminated. U.S. scientists continue meetings with University of West Brittany.

April 7 U.S. scientists meet with Dr. Cabioch at Roscoff biological station.

April 8 Fixed-wing aircraft observations reveal new areas of impact on western coast and beaches facing northeast due to 6 days of onshore winds. Considerable oil remains offshore. Subsurface beach sands are contaminated in some areas near Roscoff although surface appears clean. Areas above normal high tide are still heavily contaminated.

April 9 Sheen continues to surround vessel. Beaches on southern coast of the Brittany peninsula are clean despite reports of oil offshore.

April 11 Vessel Le Suroit returns from second cruise. Scientists indicate substantial bottom sediment contamination near Portsall and in the Bays of Lannion and Morlaix.

April 12 Patches of oil sighted off the tip of the Brittany peninsula. French officials establishing contingency plans for use of dispersants should oil move into Brest harbor area.

April 13 Oil shifting toward south. Aerial photographs indicate oil lying offshore of Brest. U.S. scientists discuss impact on kelp industry; growth of kelp appears retarded.

April 14 Observations are taken from Roscoff to les Sept Iles; major impact appears to be at Lieue de Grève where windrows of heart urchins are evident. Recent kills of molluscs are observed. Worker population appears in good health.

April 15 Overflight conducted along three transects perpendicular to the coast between the wreck and les Sept Iles. Little or no oil seen on water although some sheen and streamers observed in the vicinity of Pointe de St. Mathieu.

April 16 Some sheen reported near COB. Fifty puffins found oiled and dead south of Brest on the Crozon peninsula. Oil reported near the Ile de la Vierge, between Pointe du Raz and Rade de Brest, at Cap Sizun, between Pointe du Raz and Pointe de Lesven, and at Ile de Sein.

April 18 Oil at sea now in a number of slicks, two of which have drifted as far as 50 km south of Brest. About 7000 people now involved in cleanup.

April 19 French Navy locates 8 km diameter slick north of Ile de Sein and an 8 km x 300 m slick near Pointe du Van. Both threaten the Bay of Douarnenez.

French Naval districts issue first official estimates on fate of oil to date:

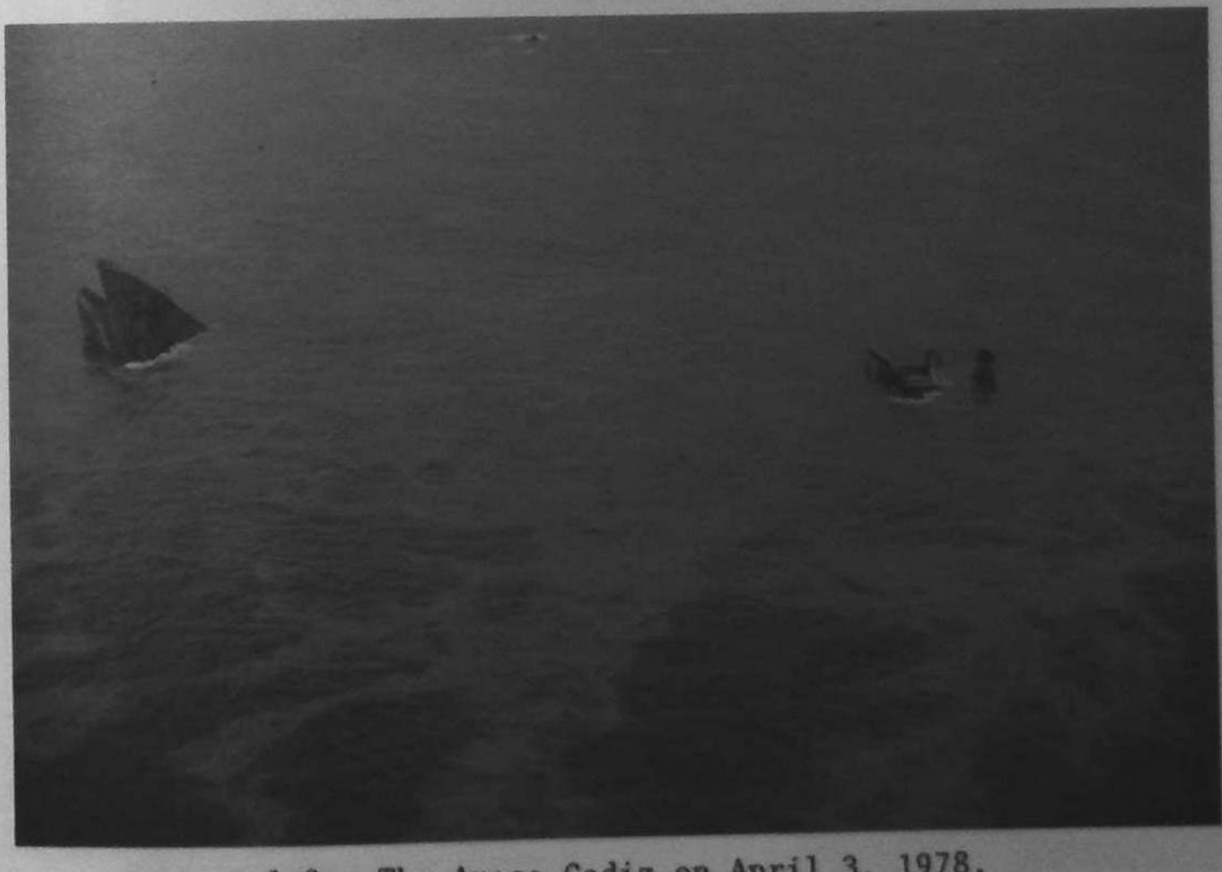
	Tons	Confidence level
1. Evaporated	74,000	± 20%
2. Amount hitting beach to date	80,000	± 50%
2a. Amount cleaned off the beaches	25-30,000	--
3. Still at sea	76,000	± 50%
This amount is broken down as follows:		
a) Treated with dispersant	20,000	± 50%
b) In process of being treated	6,000	--
c) In sediment or water column	25,000	± 50%
d) Unknown	25,000	--

April 20 Two overflights conducted by U.S. scientists. Major concentrations of oil observed near the Bay of Douarnenez and in an area 385 km south of Cap de la Chèvre. Sheen continues around wreck site early in the day, but is not evident in the afternoon.

APPENDIX B

Colored Plates

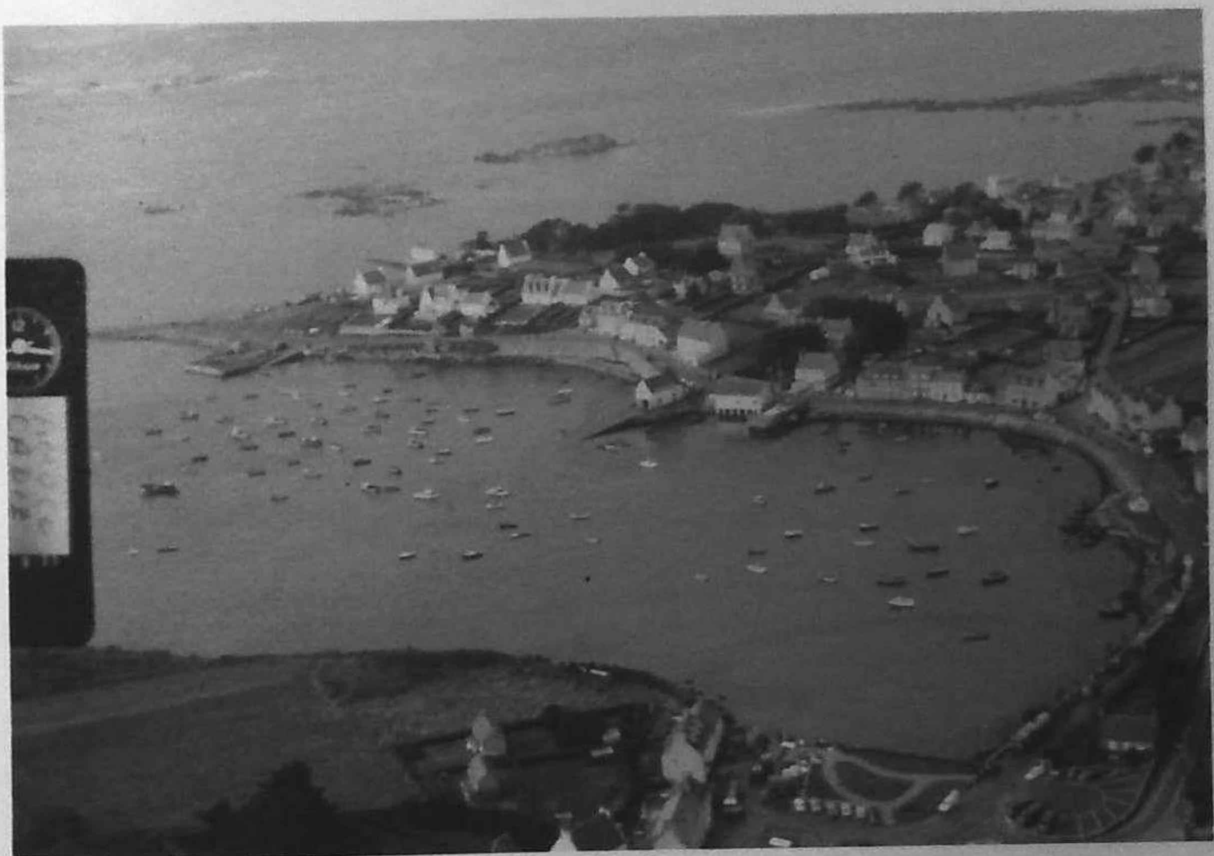
1-1. The Amoco Cadiz on March 21, 1978.



1-2. The Amoco Cadiz on April 3, 1978.

1-3. The Amoco Cadiz wreck is only about 2 km off the coast at Portsall. This section of the coast could experience heavy wave activity and frequent storms at this time of year.

1-4. Map of the northwest section of France.



1-5. The town of Portsall in Brittany.

1-6. Beach near Portsall about 2 km east of the wreck on April 2. This area has been heavily oiled repeatedly. There has been a large effort to clean up this beach. The wreck is visible in the background.

1-7. A beach about 2 km west of Portsall on April 2. This beach has received very little oil because it is west of the wreck.

2-1. Heavy mousse concentration in deep water under moderate wind conditions.

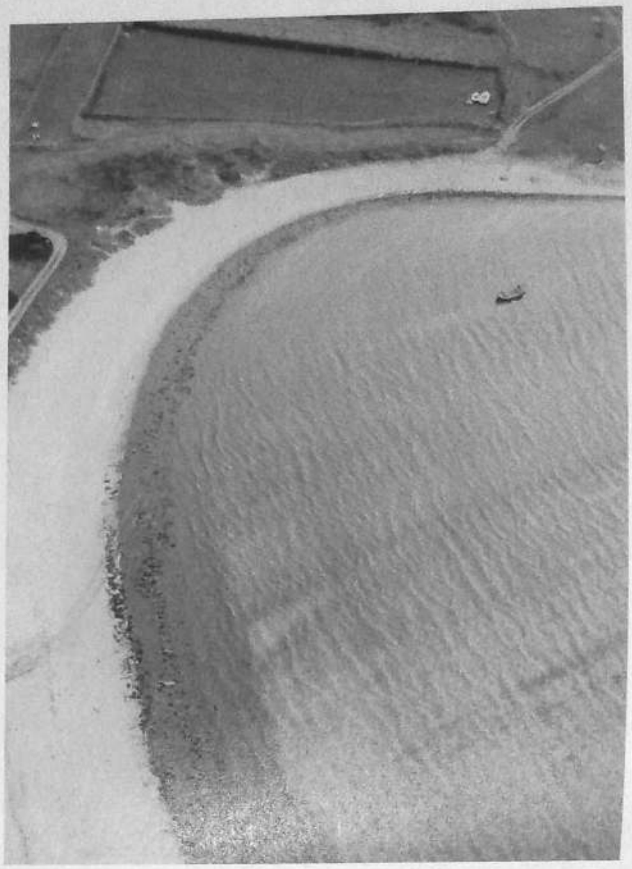
2-2. Mousse and sheen distribution in offshore region under strong wind conditions (40 kn).

2-3. Weathered mousse at sea, 31 March. Le Suroit cruise.

2-4. Frothy form of mousse seen in surf zone.

2-5. Pool of mousse accumulating along shore line.

2-6. Stream of oil moving downwind between rocks.

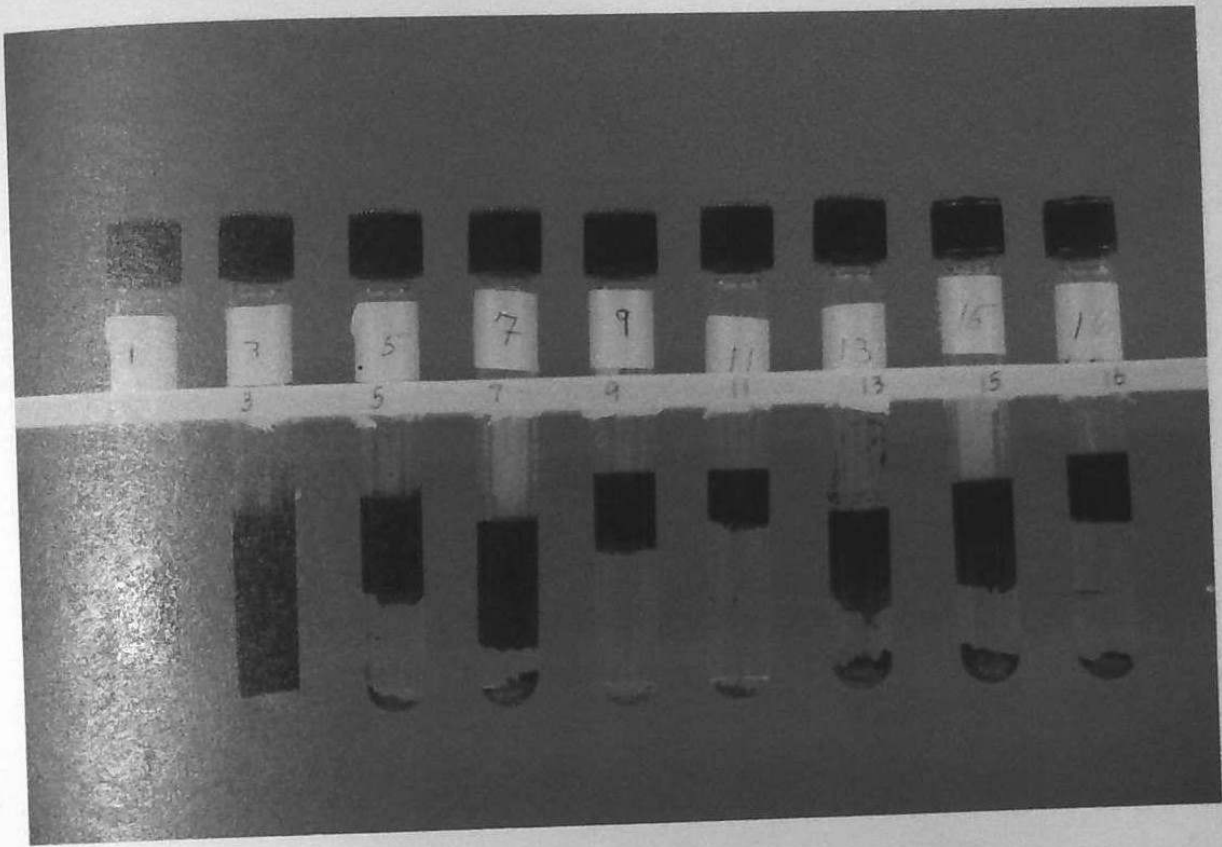


2-7. Oil moving in along-shore drift being fed by wind-blown sheen and mousse from offshore.

2-8. Oil concentration overflowing a small bay and moving into along-shore drift.

2-9. Mousse draining down beach face after being stranded by high tide.

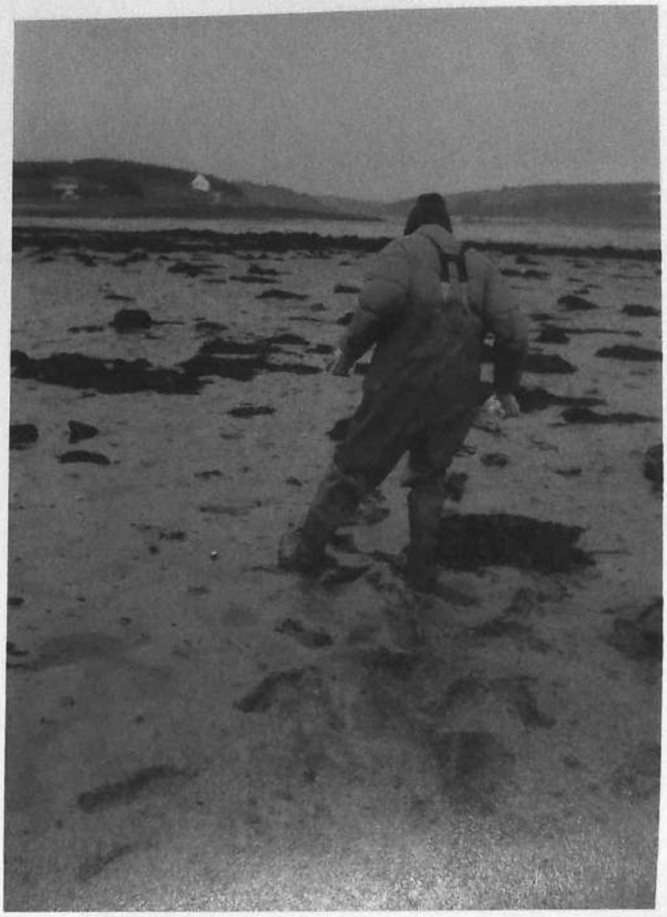
2-10. Significant amounts of mousse being washed, or refloated off rock during flood tide.



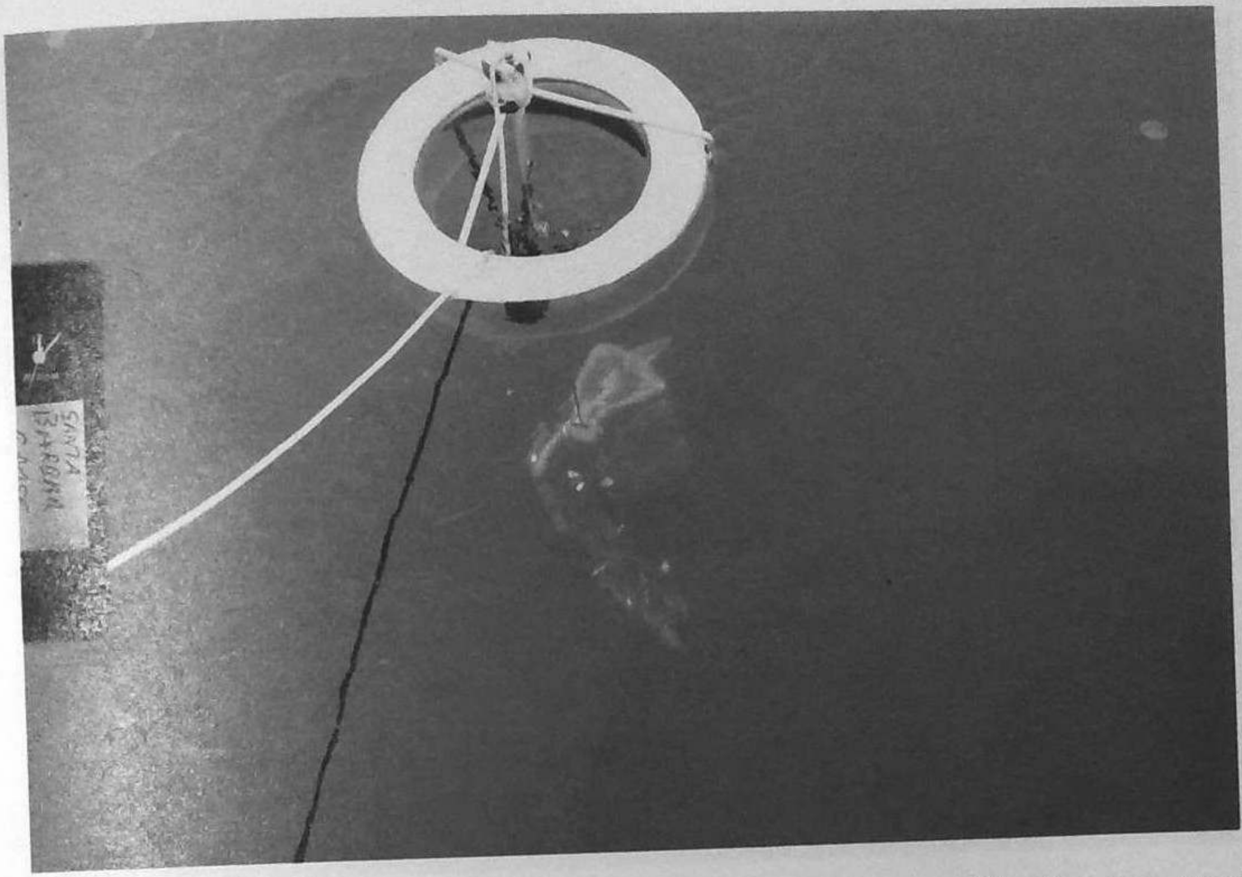
3-1. Separation of mousse samples into oil and water in the laboratory.

3-2. The French research ship Le Suroit loading equipment in preparation for chemistry cruise.

3-3. Taking water samples for chemistry analysis using niskin bottles.



3-4. Dr. Marchand of COB carrying out hydrocarbon extractions and UV fluorescence scans on board Le Suroit.

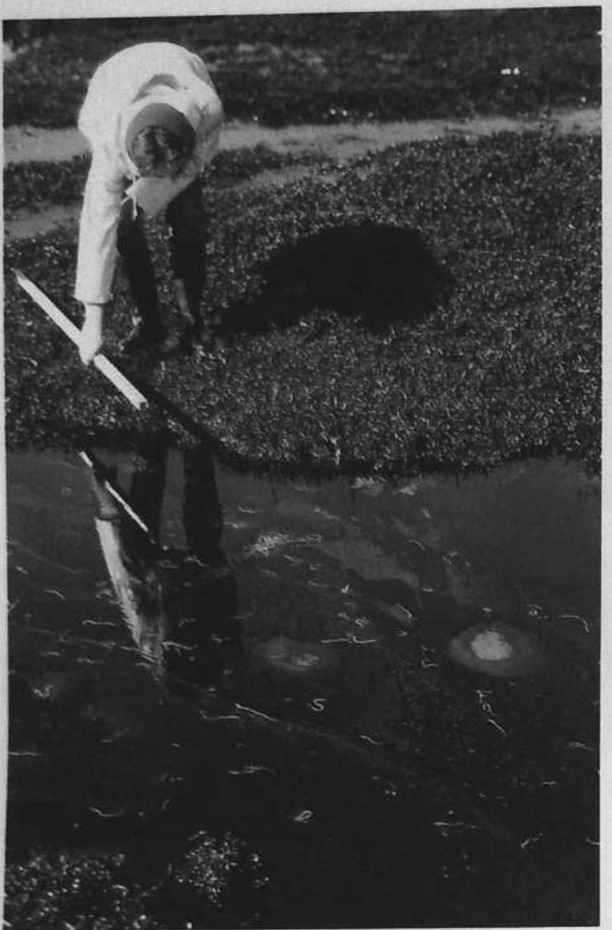


3-5. Sterile bag Butterfly sampler suspended from a float ring ready to take subsurface water sample.

3-6. Dr. Calder taking sediment samples in l'Aber Wrac'h.

3-7. Detergents being used on rocks at Santec.

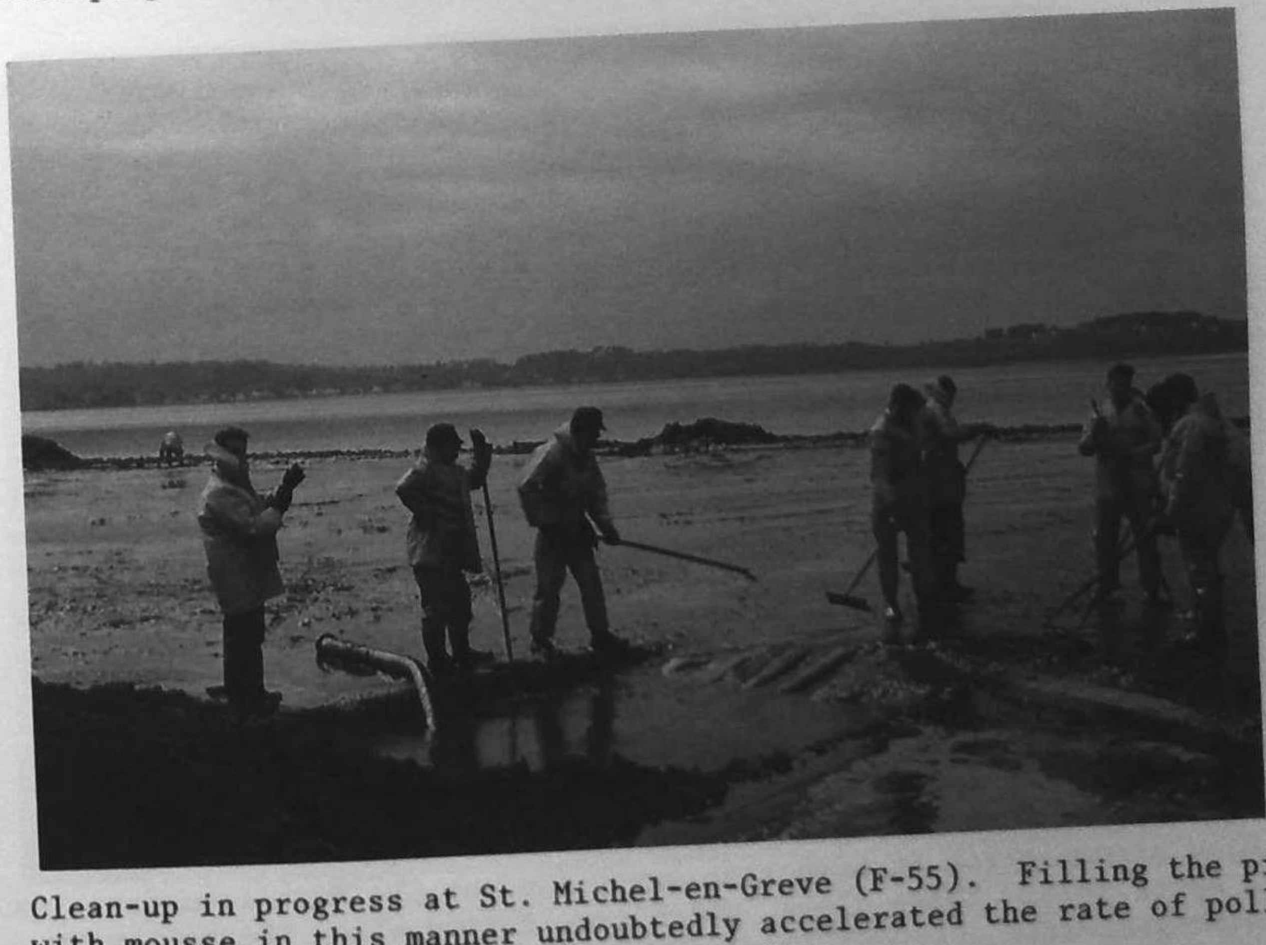
4-1. Heavily oiled marsh behind Ile Grande (AMC-18). This was the most heavily impacted salt marsh in the study area. Detailed studies were carried out in the marsh area left of the bridge. (30 March 1978)



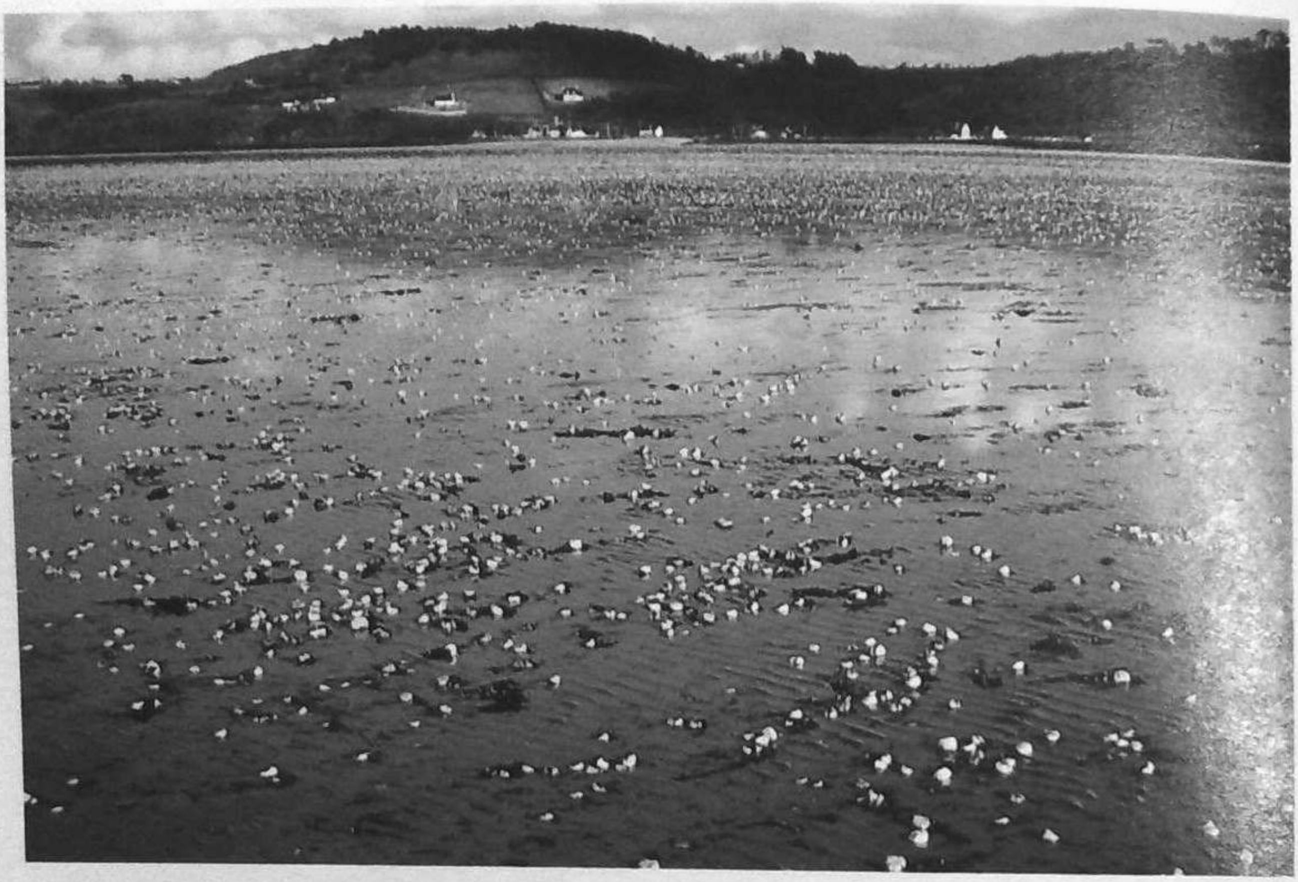
4-2. Oiled marsh grasses and dead polychaete worms within a mousse pool on the surface of the marsh at Ile Grande (AMC-18). The pool is 15-20 cm deep. (2 April 1978)

4-3. Mousse in tidal creek at Ile Grande marsh. Photograph was taken at low tide. The mousse flow is caused by late stage drainage of the marsh. (2 April 1978)

4-4. Pitted beach at St. Michel-en-Greve on 2 April 1978. Pits were dug in order that the mousse could be scraped into them with rakes. Oil was then pumped into tanks and hauled to disposal sites.



4-5. Clean-up in progress at St. Michel-en-Greve (F-55). Filling the pits with mousse in this manner undoubtedly accelerated the rate of pollution of the ground water under the beach.



4-6. Dead heart urchins on intertidal surface at St. Michel-en-Greve on 2 April 1978. The urchins, which floated freely on the water's surface, were distributed evenly over the intertidal zone as the tide receded.

4-7. Clam accumulation at high tide swash line at St. Michel-en-Greve on 2 April 1978. These clams, which were rolled along the bottom by wave-generated currents, were deposited at the middle level of swash action at high tide.

4-8. Front-end loader scooping sand at Les Dunes-West (AMC-5). In this case, a considerable amount of sand is being removed from the beach, a practice that should be avoided if at all possible. (31 March 1978)

4-9. Deployment of skimmer at Portsall (AMC-2). (20 March 1978)

10. Heavily oiled beach and low-tide terrace near Roscoff. Linear pattern perpendicular to beach is caused by ground water runoff. (21 March 1978)

4-11. Heavily oiled beach near Ile Grande. Note presence of mousse in the surf (low-tide photograph). This mousse moved back and forth across the beach with each change of the tide. (30 March 1978)

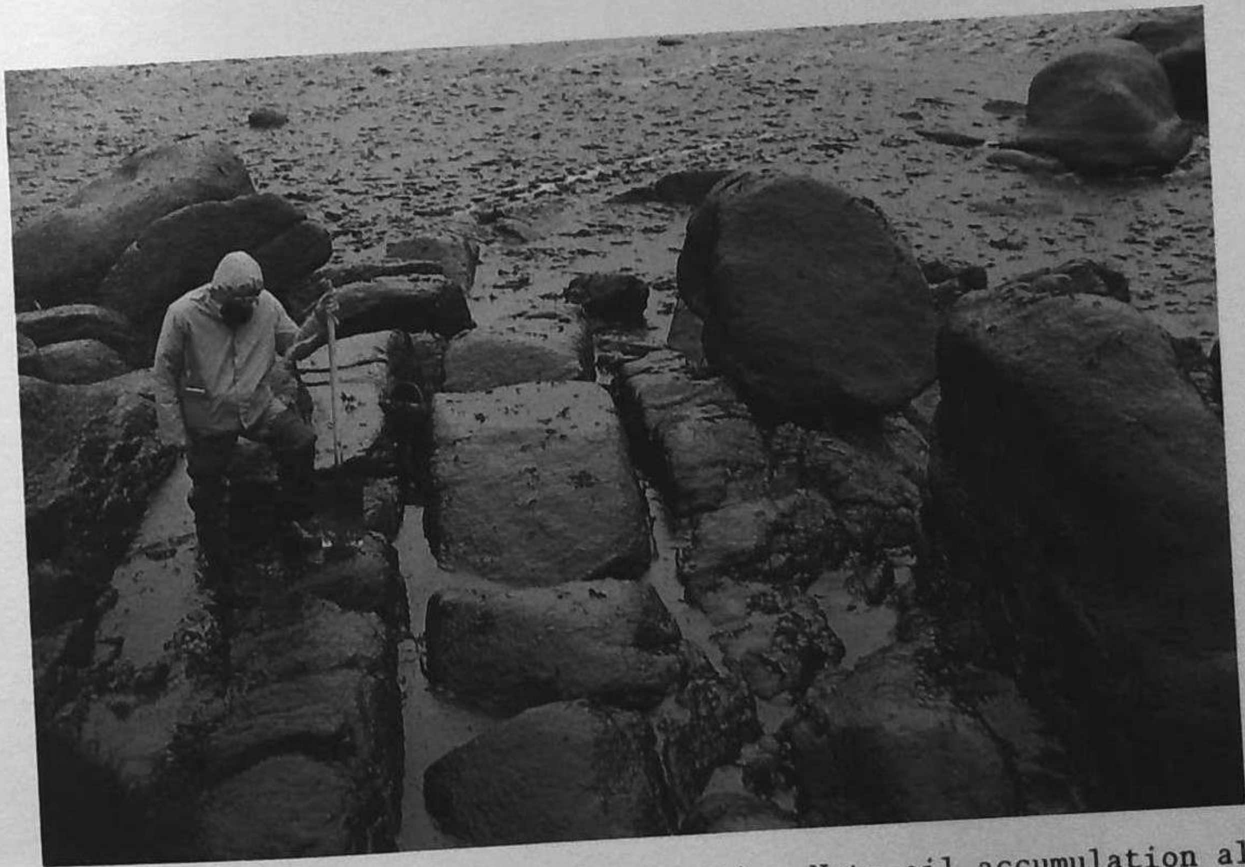
4-12. Oil swash lines on beach near Kerlouan (F-47). This beach resembles the coarse-sand beaches on Cape Cod. (27 March 1978)

4-13. Oiled beach at St. Michel-en-Greve (AMC-15). The heavily oiled gravel and rocks at the spring high tide level will prove to be very difficult to clean. (28 March 1978)

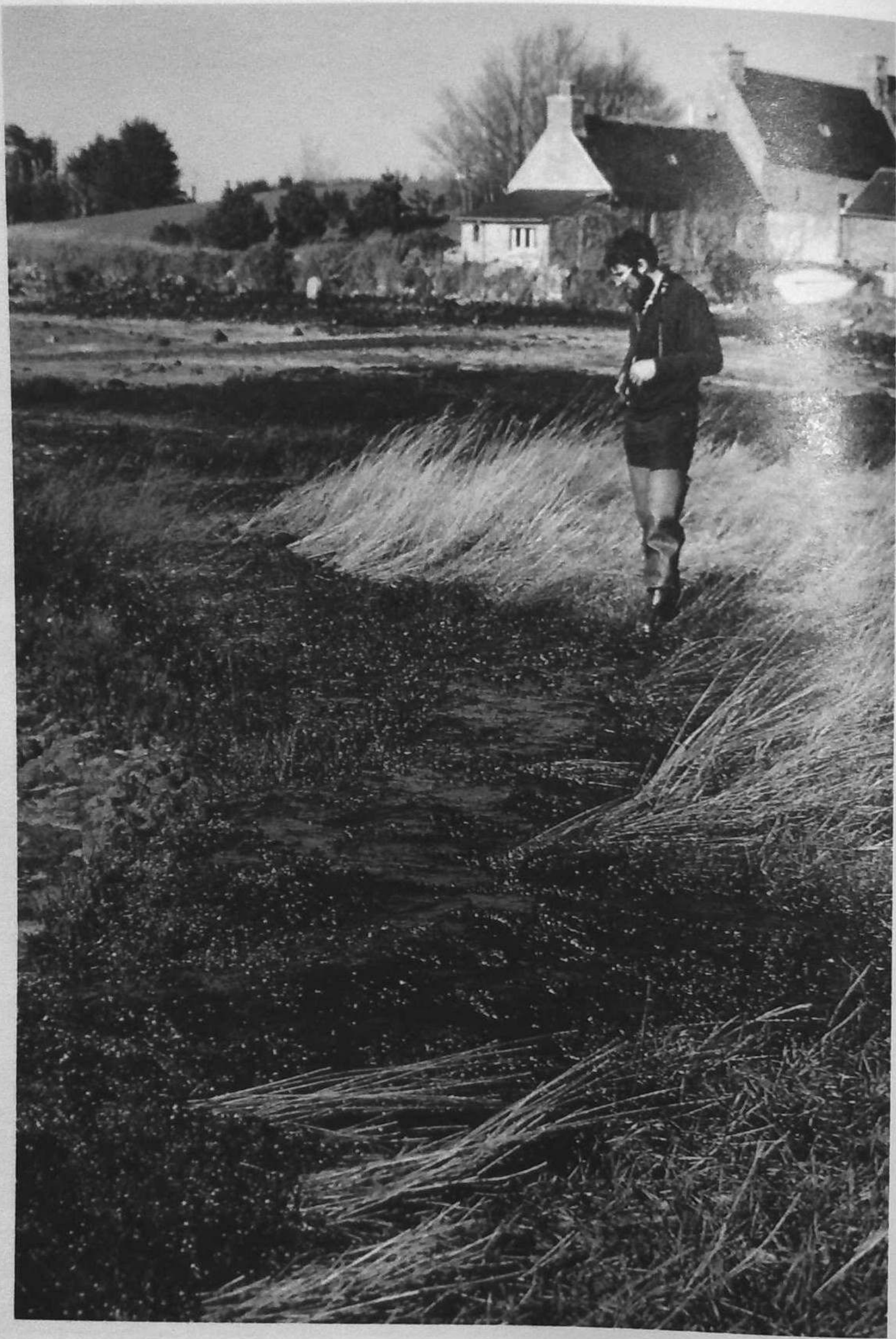
4-14. Heavily oiled gravel beach at Pointe de Sehar (AMC-16). This steep gravel beach resembles many gravel beaches in New England and Alaska. (28 March 1978)

4-15. Mousse on gravel beach at Pointe de Sehar (AMC-16). (28 March 1978)

4-16. Heavily oiled beach at Roc'h Quelennec (AMC-13). Shovel sits in oil-filled scour pool beside boulder. (27 March 1978)



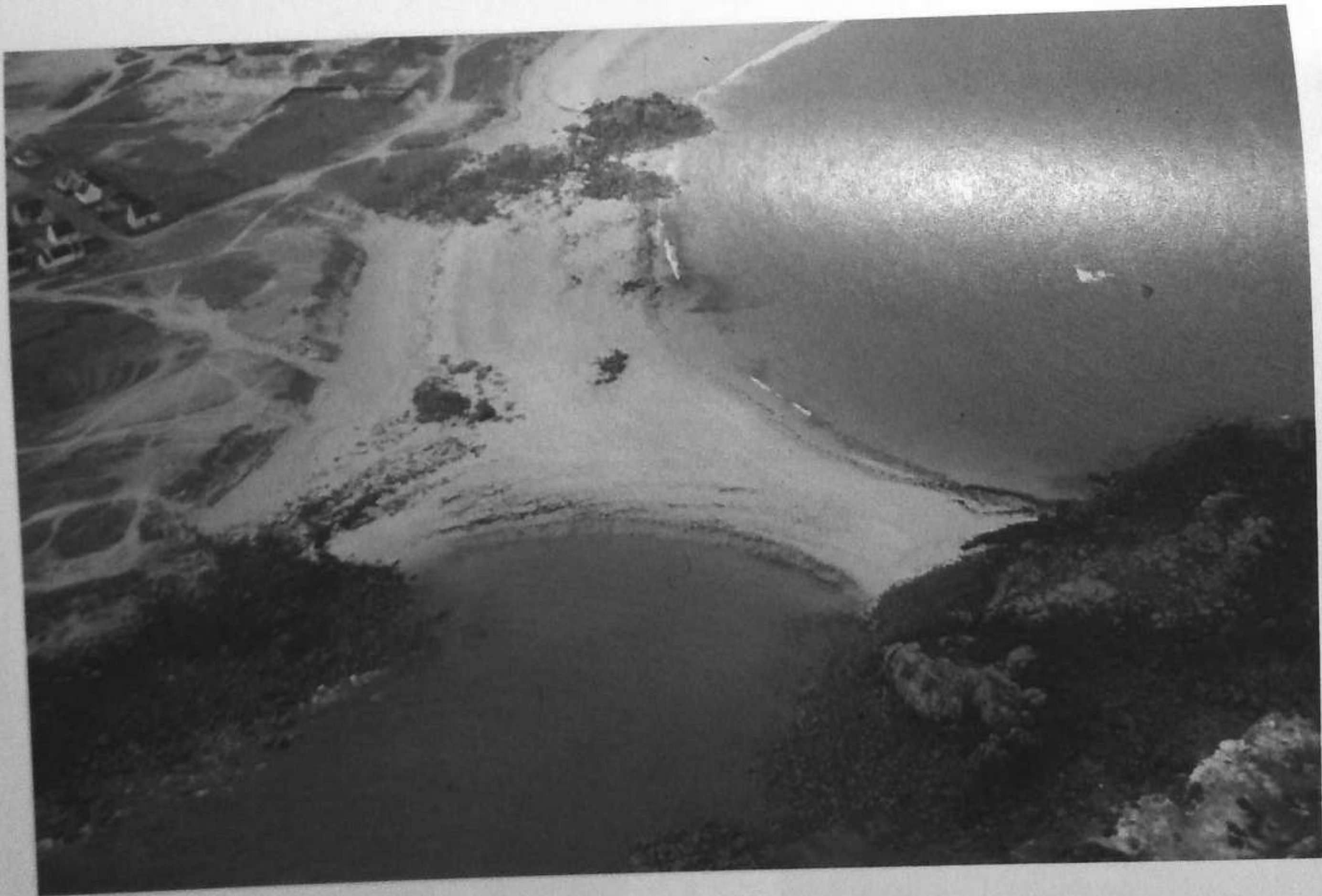
4-17. Oiled rocks at Roc'h Quelennec (AMC-13). Note oil accumulation along bedding surfaces in the rocks. (27 March 1978)



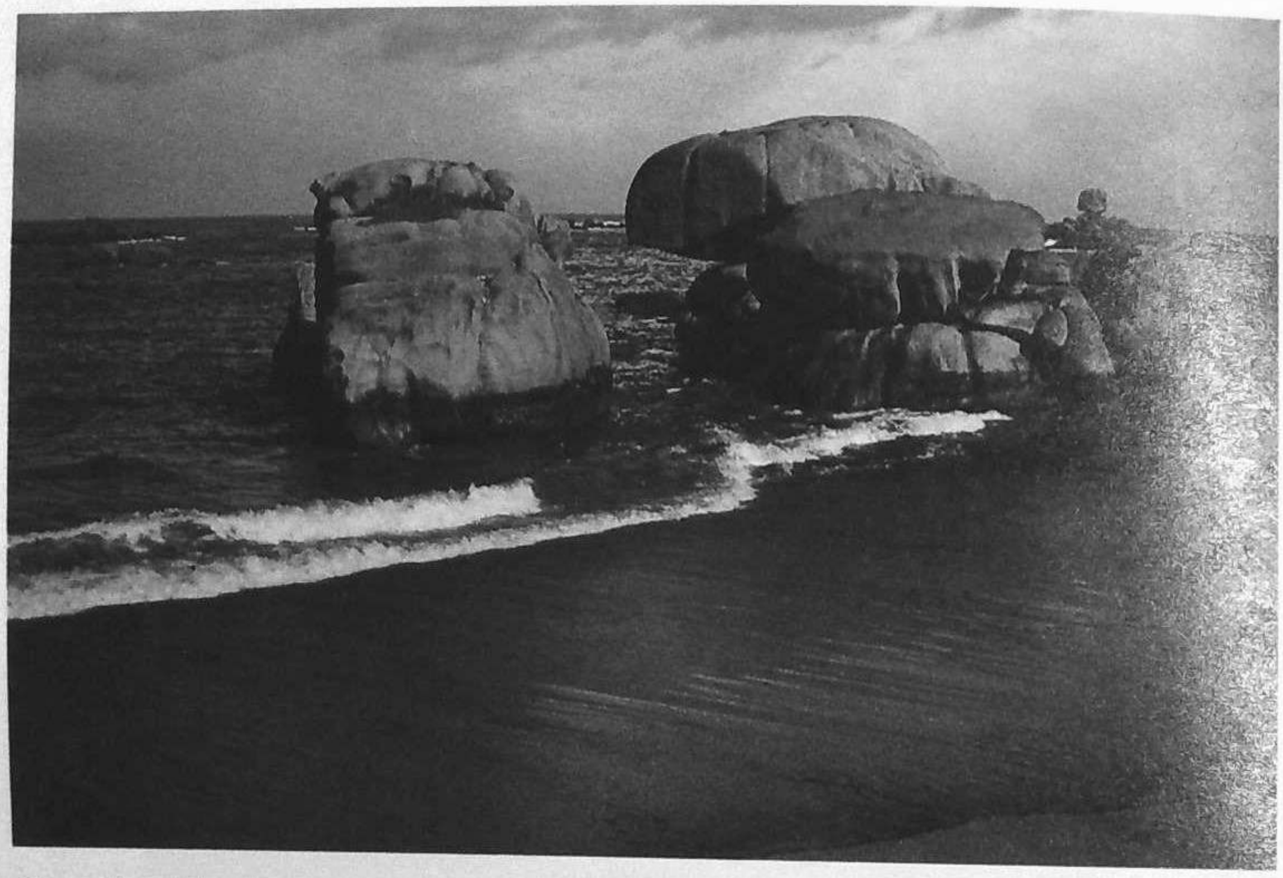
4-18. Oiled marsh near Pellinic (F-70). (29 March 1978)

4-19. Oiled seawall at Portsall (AMC-1). (31 March 1978)

4-20. Crenulate bays. There are several bays of this type in the oiled area.



4-21. Tombolo near l'Aber Wrac'h. These sand spits develop in the lee of offshore islands as a result of wave refraction around the islands. (3 April 1978)

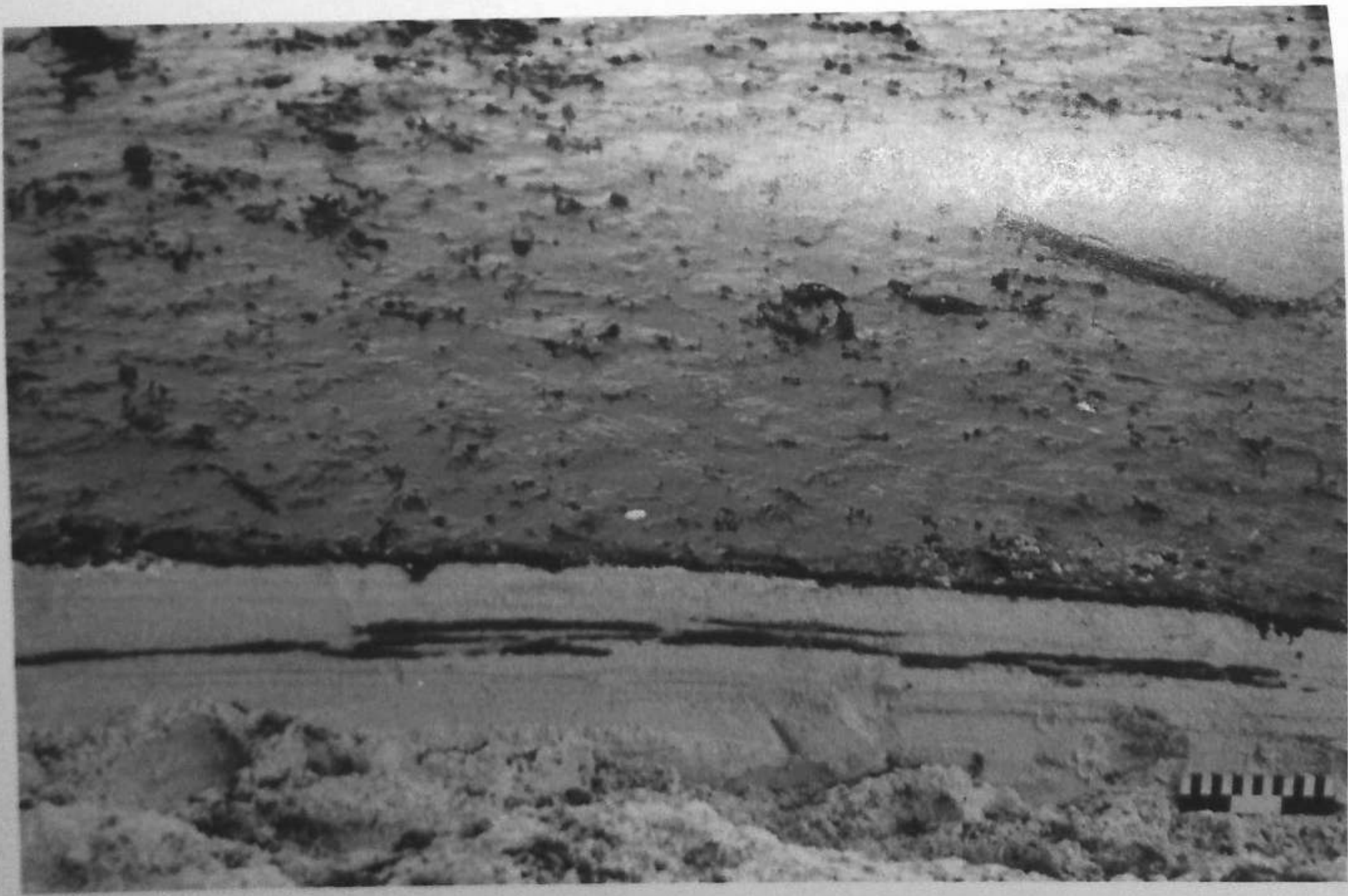


4-22. Granite blocks in intertidal zone at Coz Porz. The coast is predominantly erosional, a process which leaves these granite blocks exposed as the shoreline retreats. This area is similar in many respects to the coast of Maine. (28 March 1978)

4-23. Dune scarp at Les Dunes-West (AMC-5). Dune areas of this type are rare, occurring primarily at the mouths of streams. (31 March 1978)

4-24. Dead amphipods at high tide swash line at Les Dunes-Center. Scale units are 1 cm. (31 March 1978)

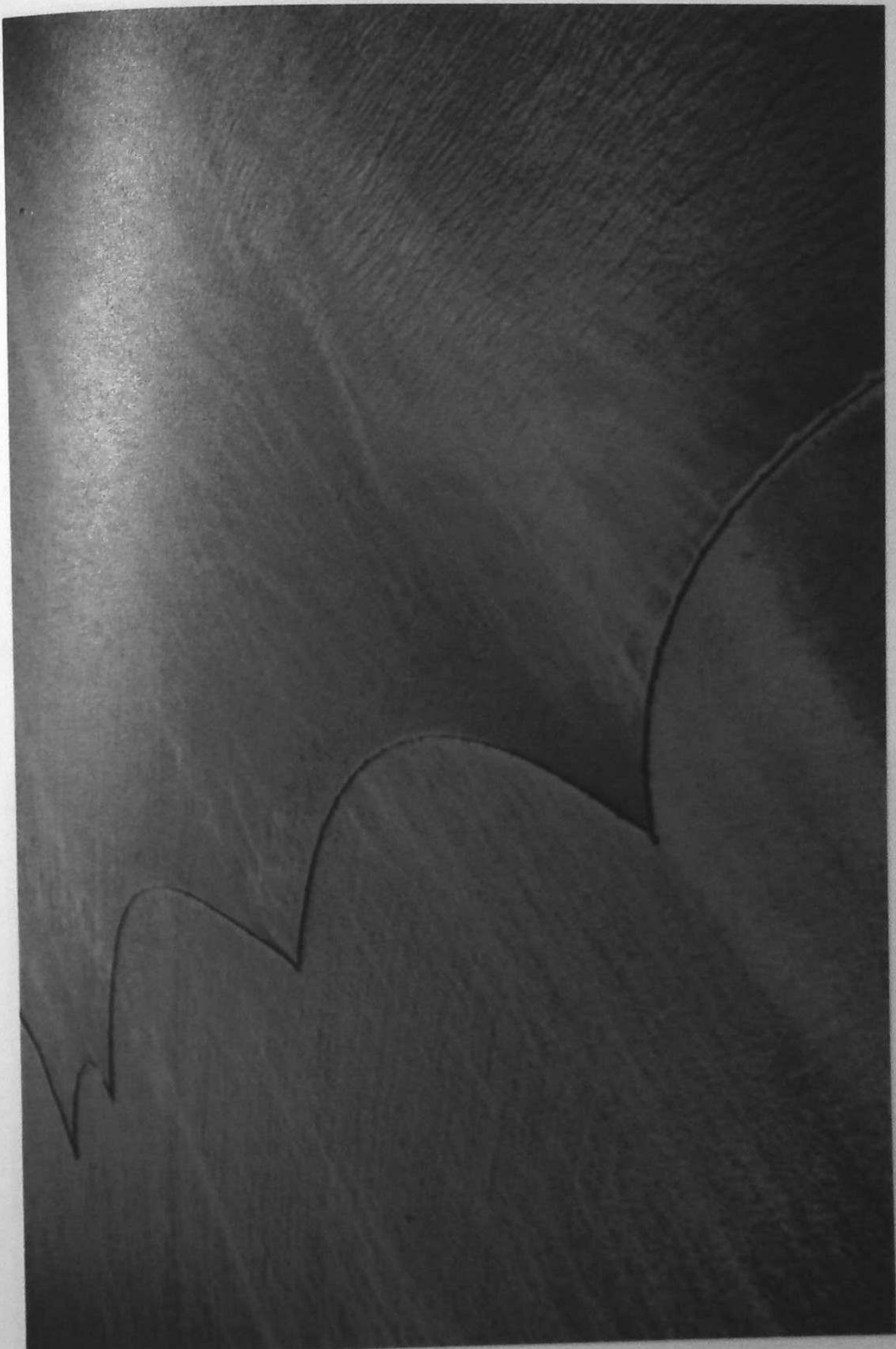
-25. Accumulation of dead cockles at the toe of the beach face at St. Cava. The dead cockles were rolled up and down the beach at high tide, finally accumulating at the toe of the beach as the tide receded. (26 March 1978)



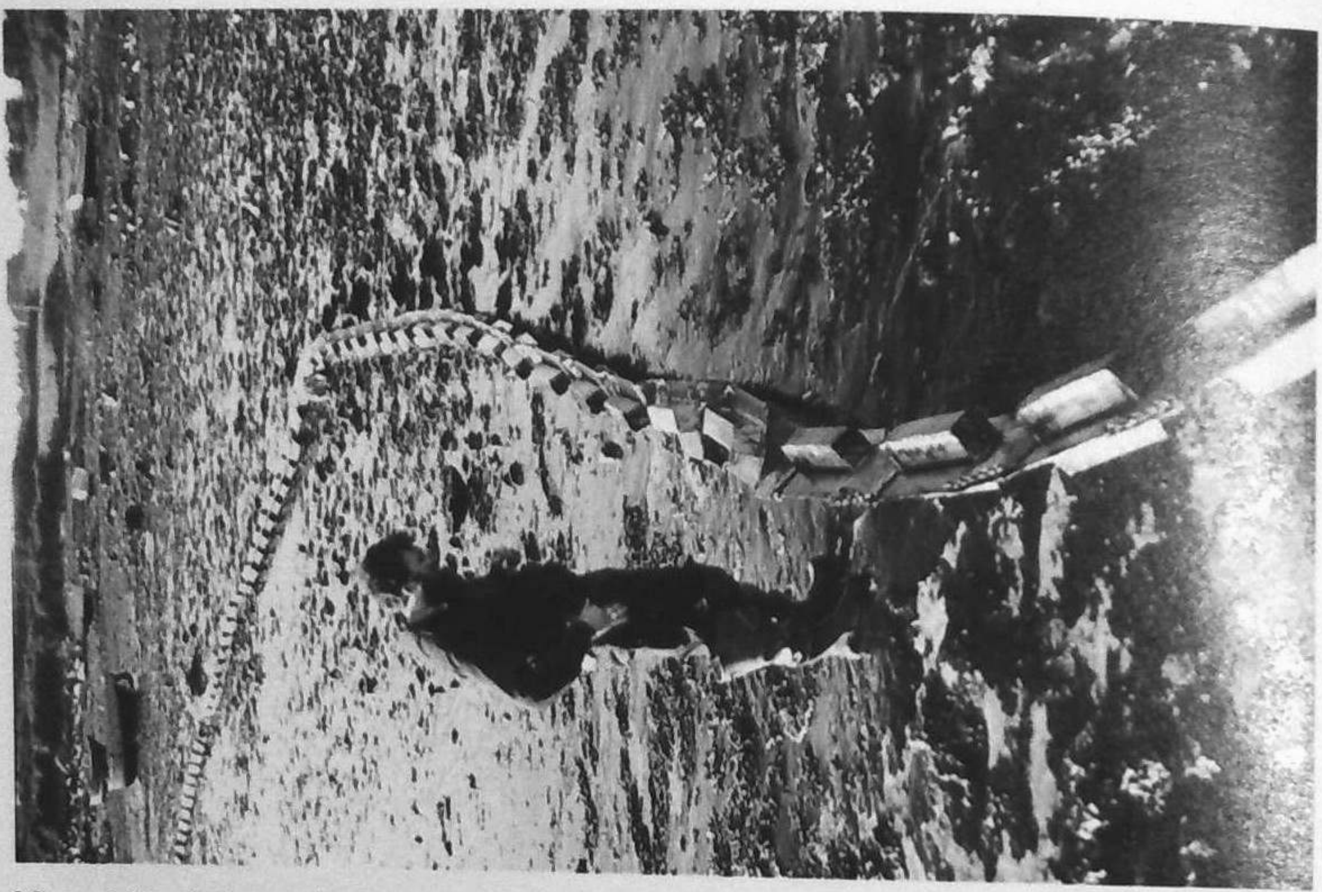
4-26. Trench though the upper portion of the beach at Cough ar Zac'h (AMC-9) showing the burial of oil layers to depths of 10-15 cm below the surface. Scale is 15 cm. (1 April 1978)

4-27. Heavy mousse in surf at Tremazan (F-1) on 20 March 1978. The mousse was gone and the rocks were clean on 31 March 1978.

4-28. Mousse being kept offshore from rocky areas by reflected waves. Near Roscoff. (30 March 1978)



4-29. Boom on sand flat (at low tide) near Kerenoc (F-75). The entire upper portion of the flat was heavily oiled. (29 March 1978)



4-30. Oil (sheens) streaming through the oil boom at the mouth of l'Aber Wrac'h. (21 March 1978)

4-31. Heavily oiled beach at Port la Chaine (AMC-17). (29 March 1978)

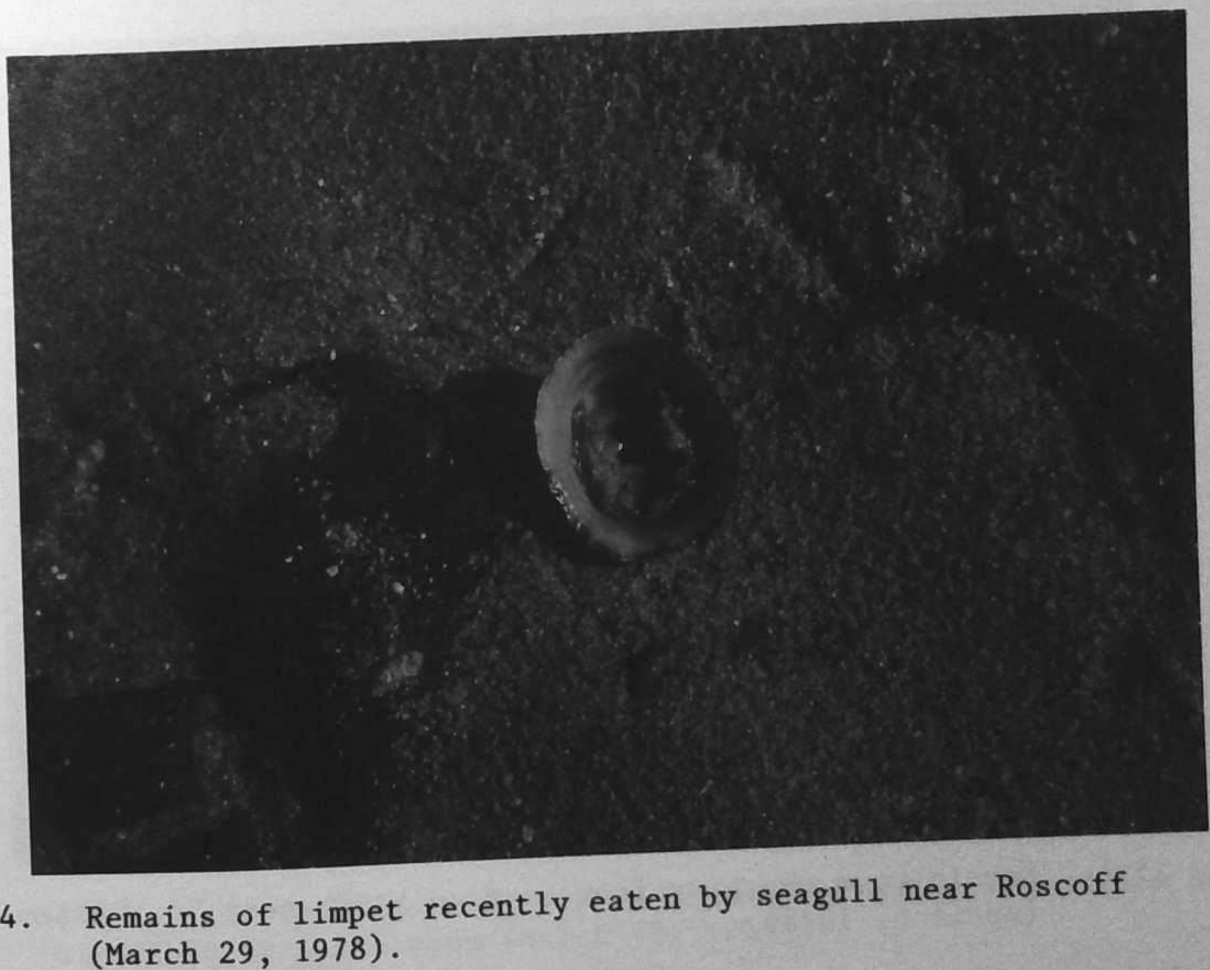
4-32. Oiled tidal flats at east Roscoff (AMC-8). (21 March 1978)

4-33. Oil on gravel beach at station 6 near Roscoff on March 24.

5-1. Petroleum in "mousse" form mixing with attached seaweeds in rocky intertidal area near Roscoff (March 29, 1978).

5-2. Recently emerged cockle (Cerastroderma sp.) in moribund stage near Roscoff (March 29, 1978).

5-3. Oiled intertidal limpets (Patella sp.) near Roscoff (March 29, 1978).



5-4. Remains of limpet recently eaten by seagull near Roscoff (March 29, 1978).

5-5. Oil in pericardium of limpets near Roscoff. Two recently killed limpets are on sand at base of rock. Limpet on rock was turned over by scientist (April 1, 1978).

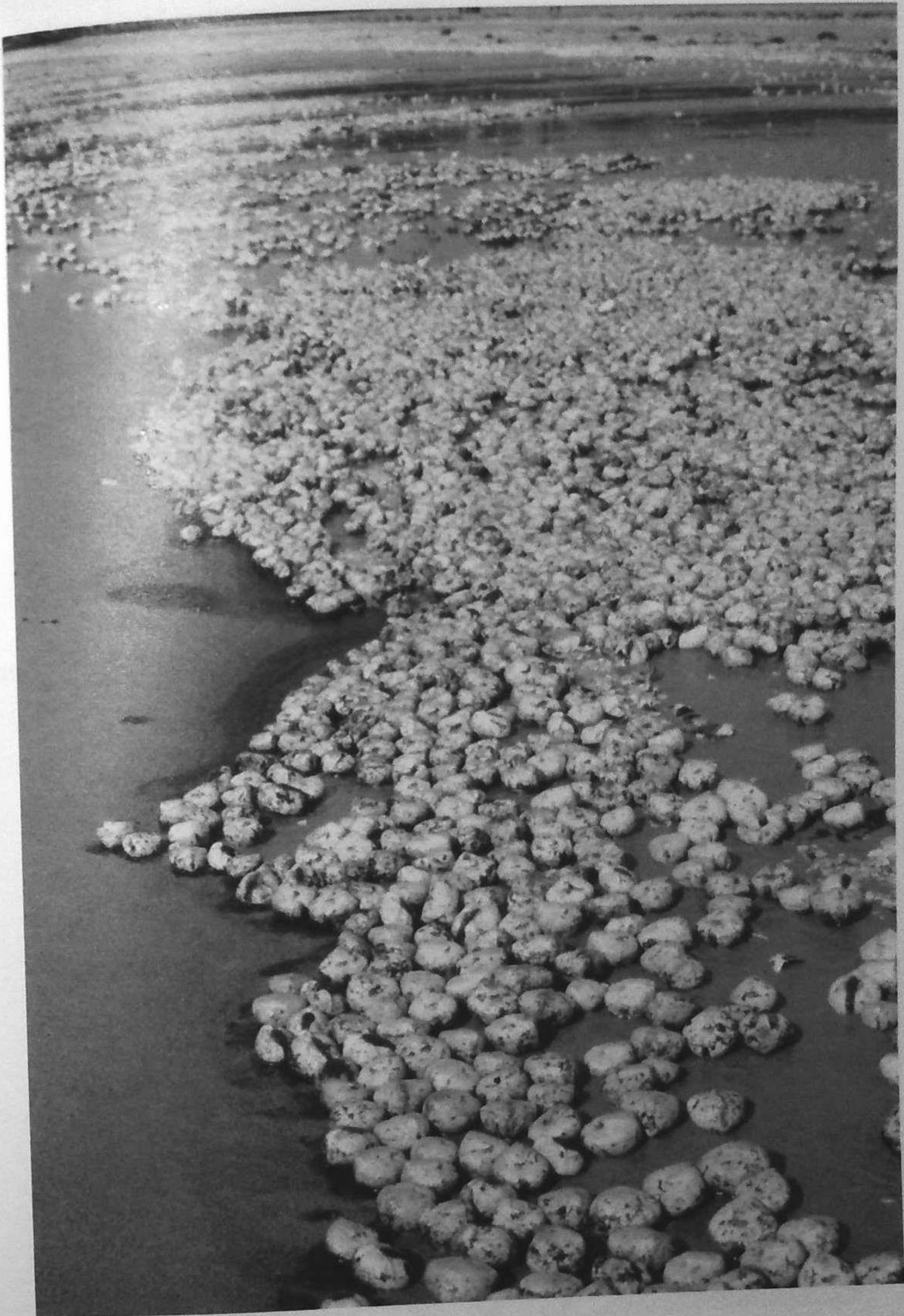
5-6. Nereid worm emerging from sand on beach near St. Efflam (April 6, 1978).

5-7. Dead crab in heavily oiled marsh near Ile Grande (March 30, 1978).

5-8. Nereid worms seeking refuge in small pool of water surrounded by oil in marsh near Ile Grande (March 30, 1978).

5-9. Mass mortality of nereid worms in marsh near Ile Grande (April 2, 1978).

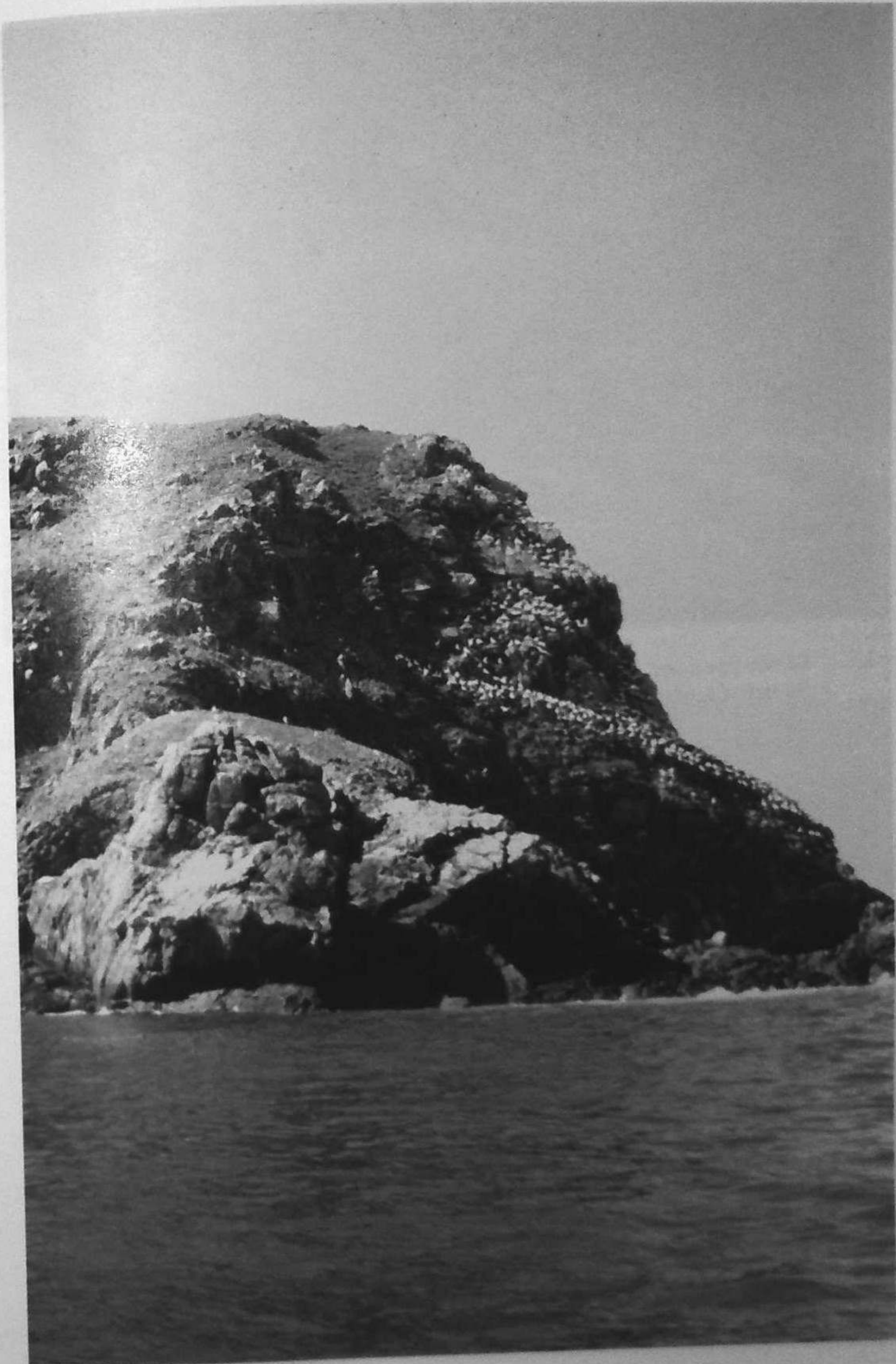
5-10. Wind rows of subtidal urchins, mollusks and other invertebrates which covered the beach from St. Efflam to St. Michel-en-Greve (April 2, 1978).



5-11. Wind rows of urchin tests on beach at St. Efflam (April 2, 1978).

5-12. The number of dead organisms was estimated from counts in several one-square-meter quadrants (April 2, 1978).

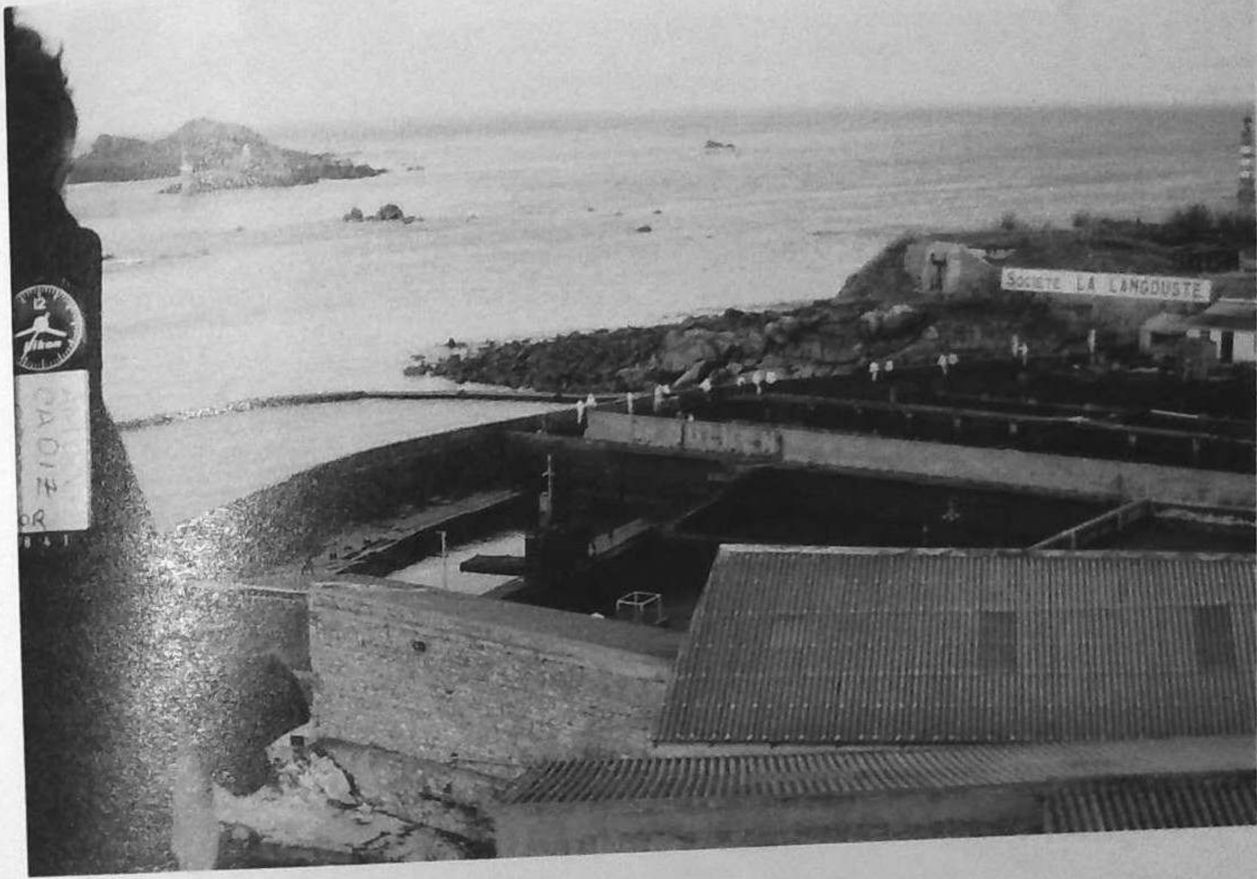
5-13. Surface and subtidal organisms alike were impacted at St. Efflam (April 2, 1978).



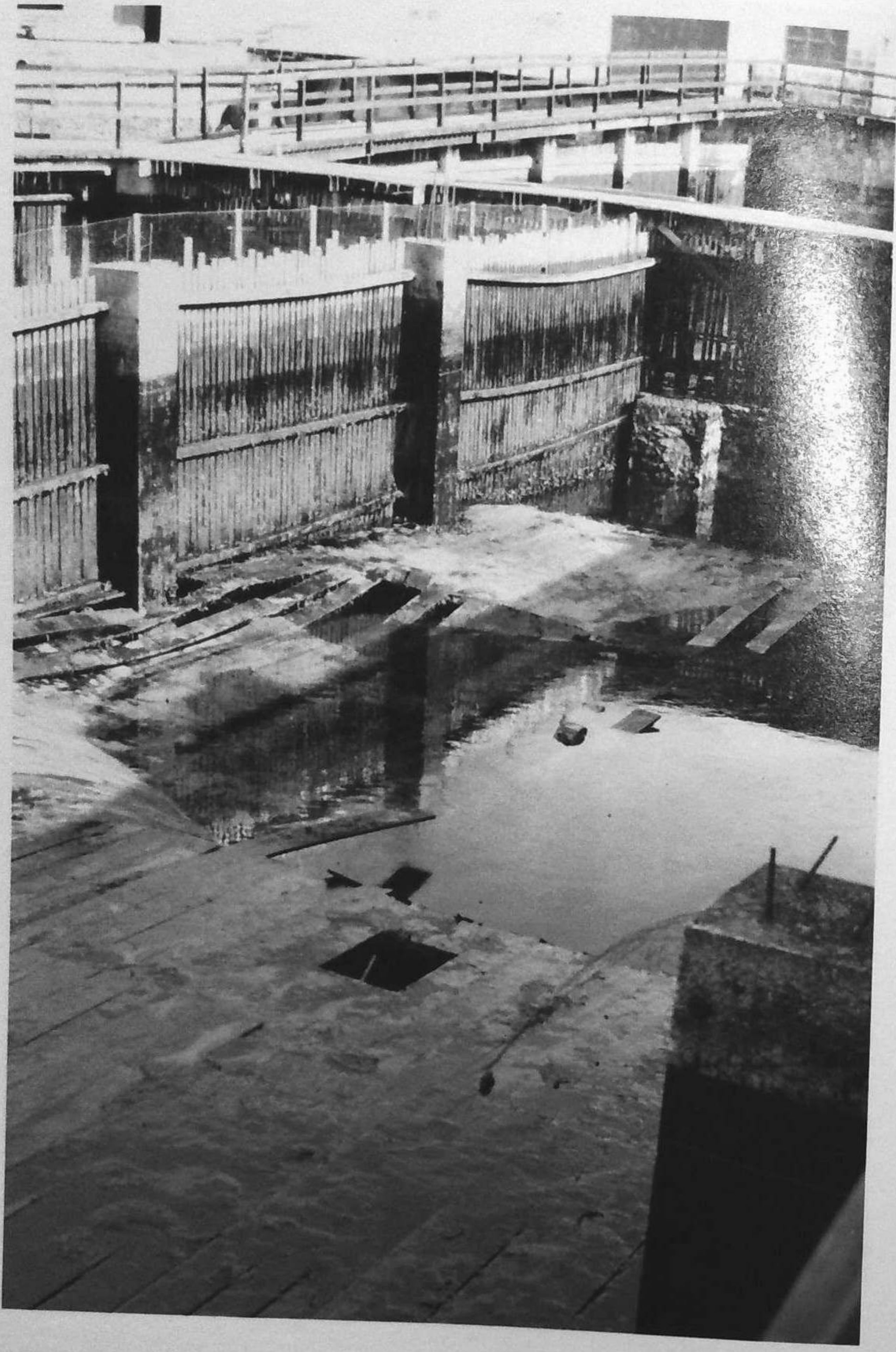
5-14. Nesting gannet colony on Rouzic Island at Les Sept Iles bird sanctuary near Perros-Guirec (April 2, 1978).

5-15. Carcasses of oiled birds being inventoried at bird hospital in Brest (April 16, 1978).

5-16. Oiled oyster farm being cleaned near St. Pabu on Aber-Benoit estuary (April 4, 1978).



5-17. Oiled lobster-holding pen at Roscoff (April 1, 1978), and aerial view.

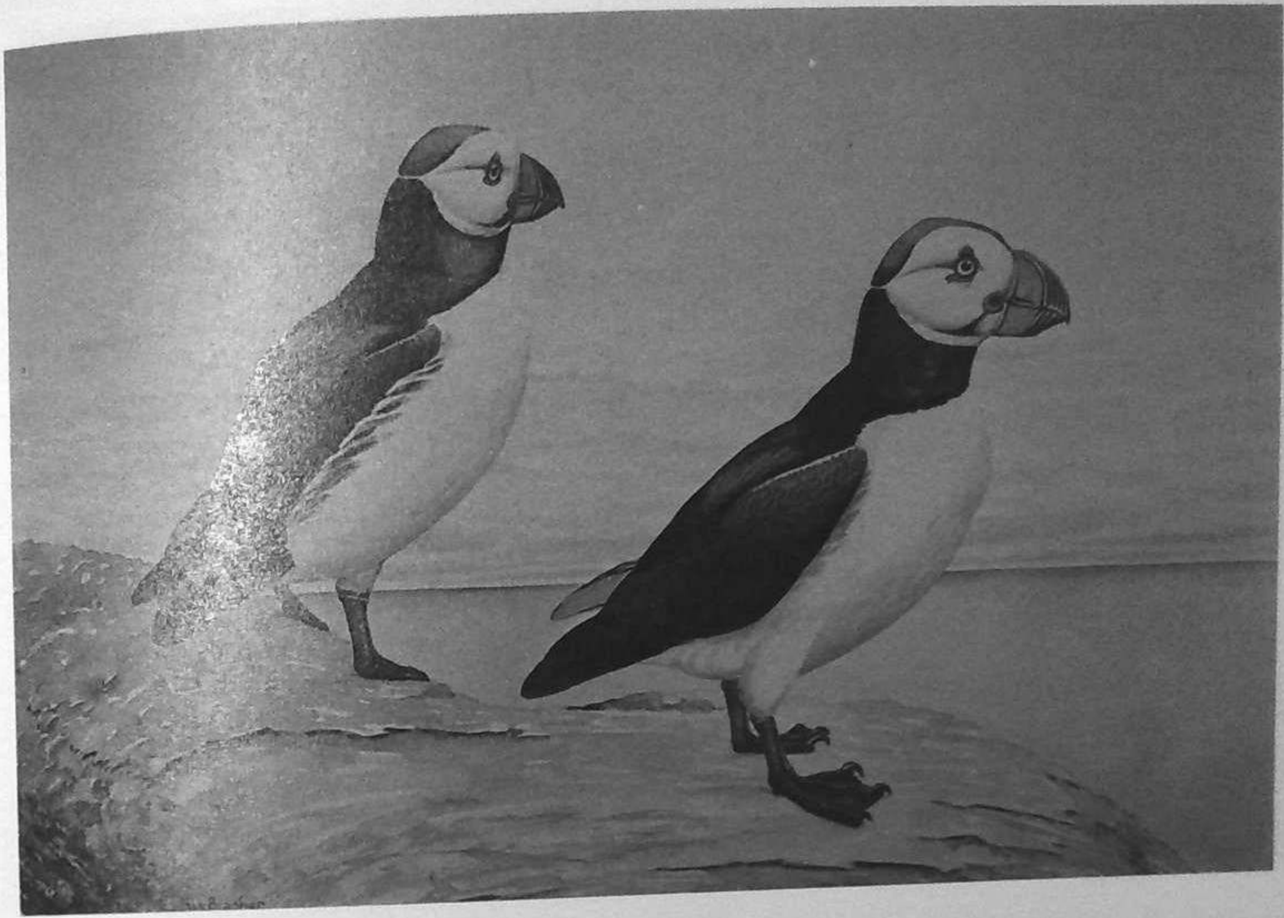


5-18. Inside view of one lobster-holding pen showing extent of oiling (April 1, 1978).

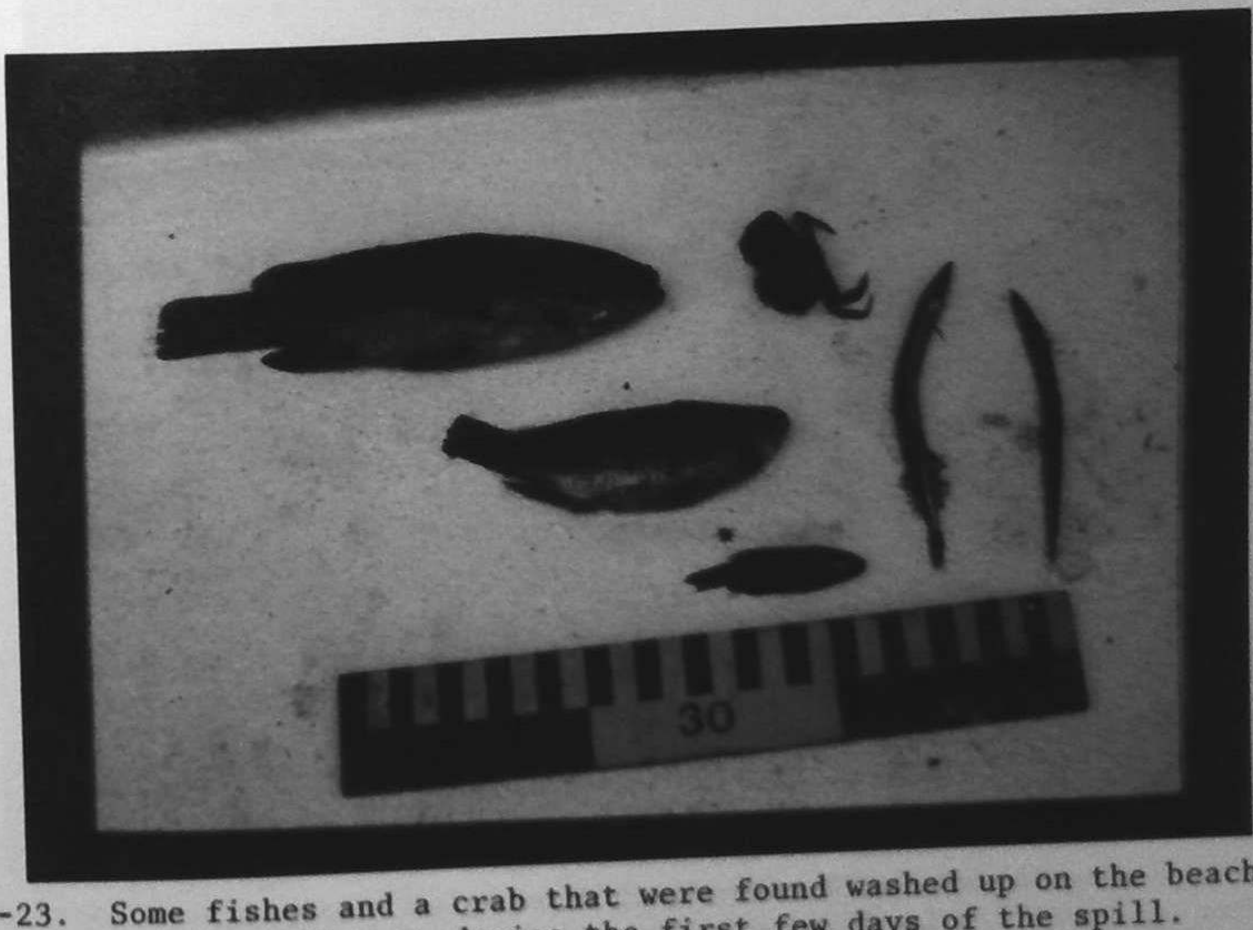
5-19. Gale force winds coupled with spring tides flung oil into cauliflower fields during harvesting process (March 30, 1978).

5-20. Oyster racks off the Brittany coast (21 March 1978).

5-21. Fishing stopped near Portsall after the wreck. Many people in the area fish part-time as a second occupation.



5-22. The common puffin.



5-23. Some fishes and a crab that were found washed up on the beach in the Portsall area during the first few days of the spill.

6-3. A simple bucket brigade was used to dip the thick mousse from the surface of the water and carry it ashore. It was stored in the 30-gallon garbage cans until a vacuum truck could pick up the oil.

6-4. Workmen remove debris from two Acme skimmers which were among the very few to be used to skim the oil from the water and pump it into tank or vacuum trucks.

6-5. Middle dunes of the beach northeast of Portsall. Soldiers working with hand tools squeegee oil into pits where it is picked up by suction lines from two honeywagons.

6-6. Workers scoop the oil into the loader bucket. The loader elevates it and dumps it into an Army dumptruck (shown in the background) for transport off the beach.

6-7. Soldiers and a front end loader are piling up oil-soaked seaweed so the oil can drain out for collection and the seaweed can be removed for disposal. This beach is just north of the Portsall harbor area.

6-8. Trenches on the beach at St. Michel-en-Greve. The trenches proved effective in collecting the oil except where the sand surface was heavily marked with vehicle tracks.

6-9. Pits created by a front-end loader are used as a receptacle for oil moved across the beach with hoes and squeegees. The oil is picked up from the pits by honeywagons for transport to interim storage areas.

6-10. The ability of the algae at the upper intertidal level to absorb large quantities of oil is demonstrated. It appears that the algae become dry during low tide and are then oil-wetted by oil on top of the incoming tide before they are water-wetted.

6-11. A group of local seaman volunteers work to remove heavy deposits of oil from a rocky area.

6-12. Soldiers work with small tin cans to remove oil from in among rocks. They then transfer the oil to successively larger containers for transport from the rocky area.

6-13. Volunteer firemen wash down steps and rocky areas with detergent solution on the beach at Perros-Guirec.

6-14. Clean-up at Portsall, 31 March 1978.

6-15. Oiled algae are removed by hand and placed in bags for disposal.

6-16. A group of local women work with a company of soldiers to collect oil in the marsh at Ile Grande for removal.

6-17. Oil/water/seaweed separation station and interim storage near Roscoff. A lesson learned from the spill is that a large interim storage has to be created, because the logistics train cannot handle the large volumes of oil removed from the water and beaches.

6-18. Close-up of the separation pits shown in Fig. 6-17. Note the use of dual pits with a screen between to separate the seaweed from the mousse.

6-19. A vacuum truck decants water collected along with the oil. Much effort was lost early in the spill by failure to properly decant tankage.

6-20. A small coastal tanker is loaded with the oil/water mousse removed from the water's surface and the beaches. Note the large backlog of trucks waiting to be loaded.

6-21. One of six ultimate disposal pits prepared in a clay area near the coastal town of Tregastel. Chemical stabilization has been considered for this material.

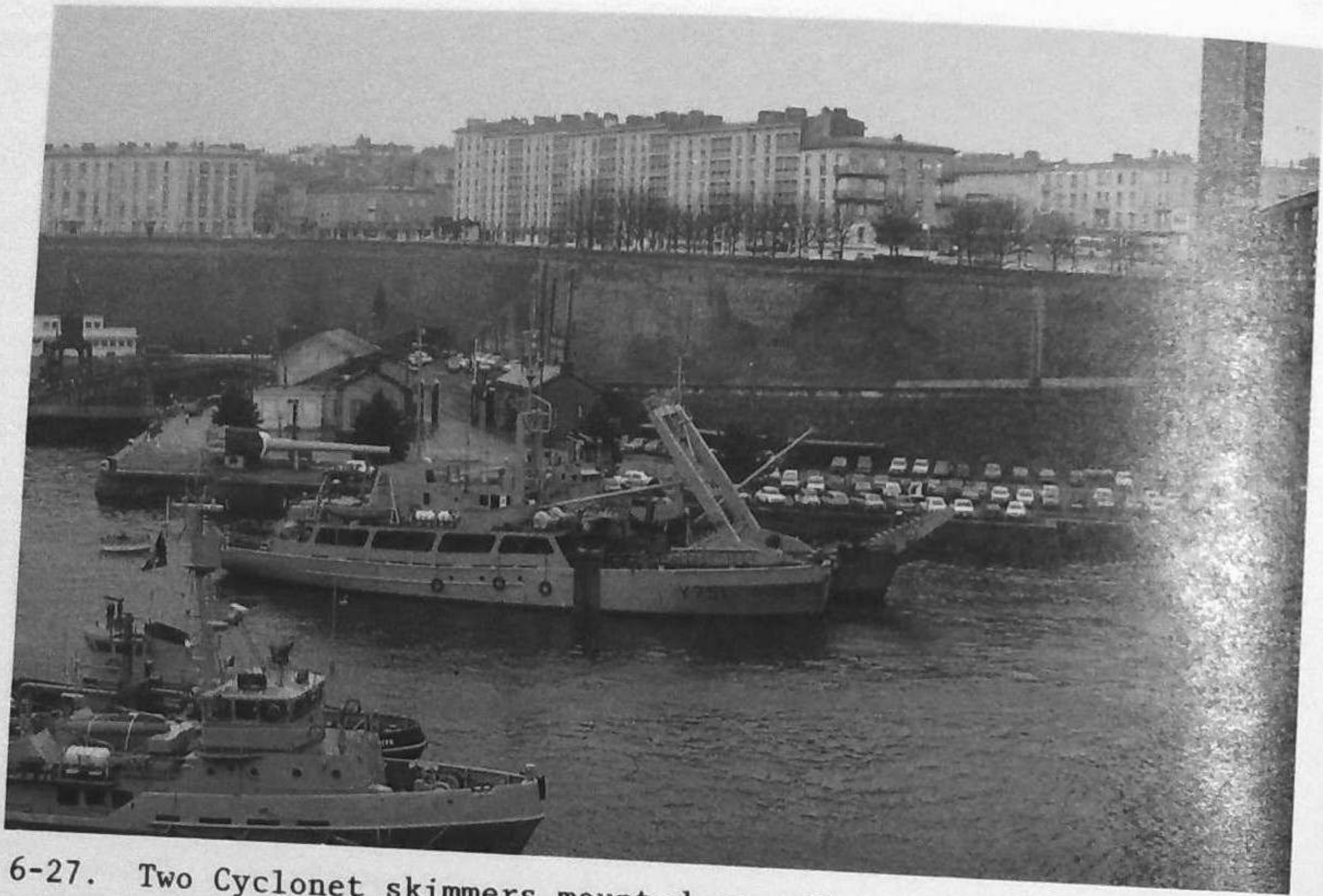
6-22. Close-up of material delivered to storage basins near Brest Harbor. The plastic bags used to transport the algae and oiled sand are a hindrance to either burning or chemical stabilization of the residual material.

6-23. Unemptied disposal pits were left on St. Michel-en-Greve beach. Digging through some 4 inches of recently deposited clean sand yielded an oil mousse layer 6 to 8 inches thick.

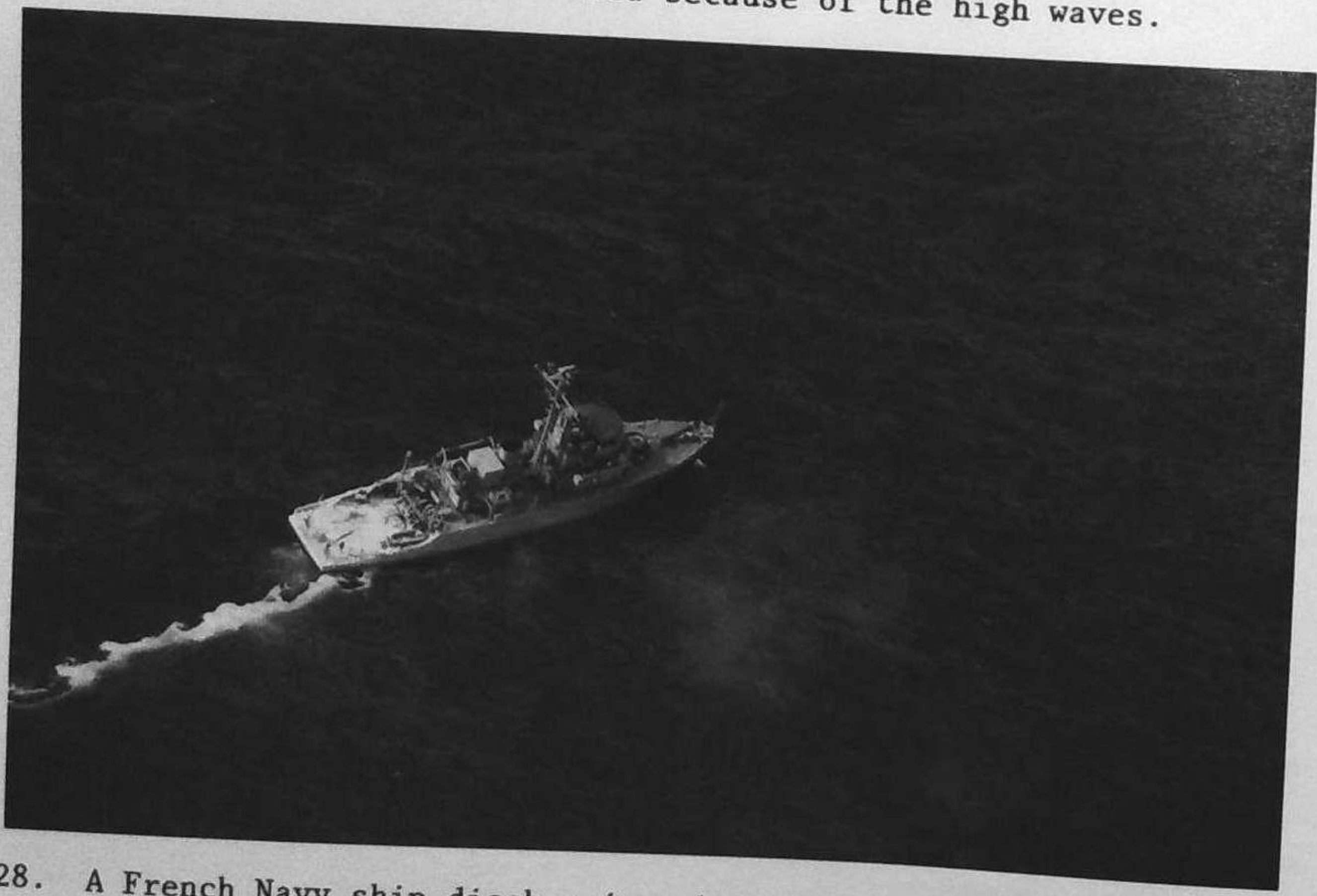
6-24. The result of the extensive use of mechanized equipment on St. Michel-en-Greve beach is evident here.

6-25. Close-up of the oiled sands at St. Michel-en-Greve. Shown are the oiled sand at the surface and the various oiled sand layers that have resulted from the deposition of sand and oil since the oil first reached this spot.

6-26. In the early stages of the spill, booms were not effective. However, booms deployed later across some harbor entrances and adequately tended reduced the amount of oil entering these systems.



6-27. Two Cyclonet skimmers mounted on a French Navy ship in Brest Harbor. Such large expensive skimmers did not prove useful. A large barge could use Cyclonet skimmers for only about two hours in the Roscoff area because of the high waves.



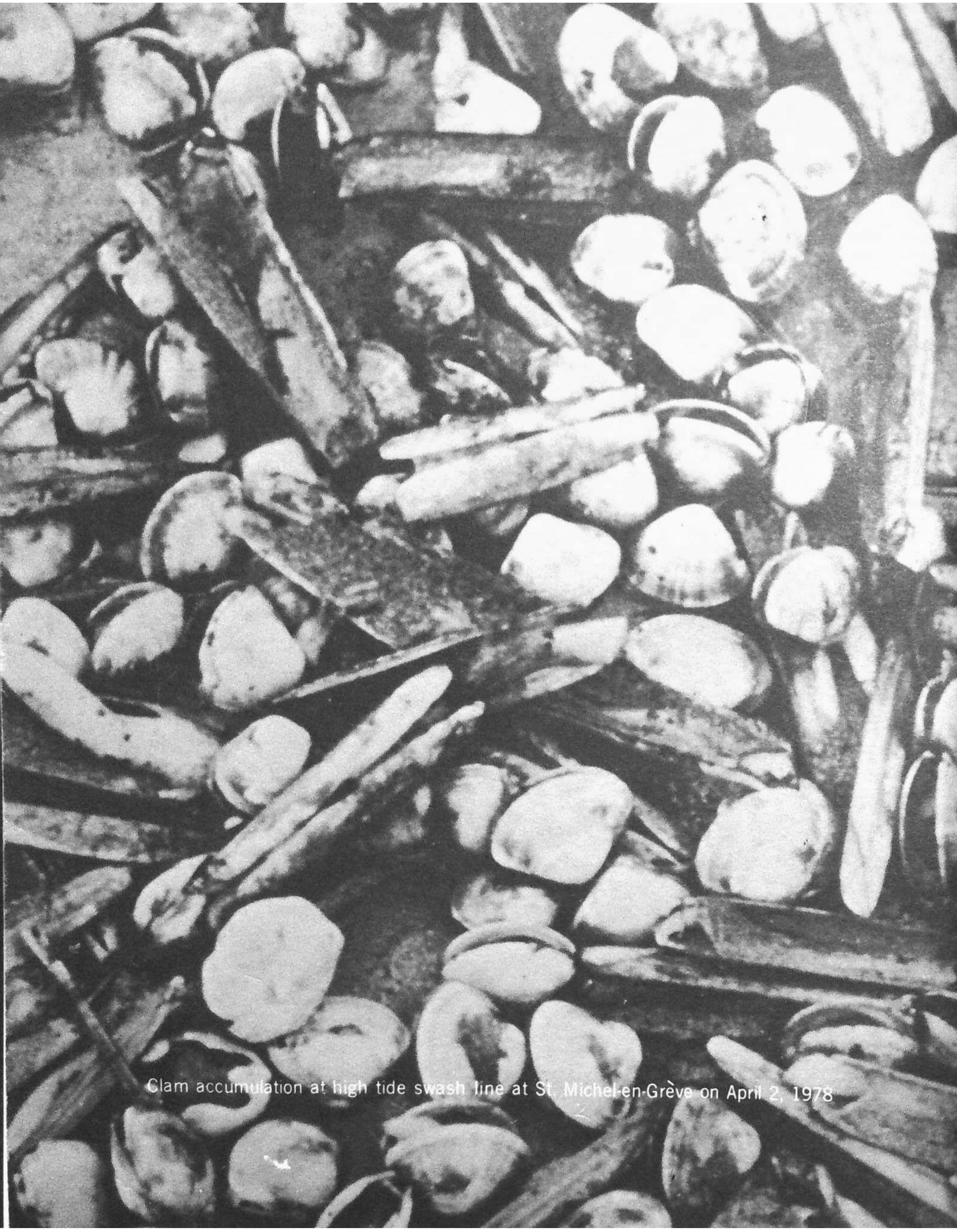
6-28. A French Navy ship discharging chalk onto patches of mousse. The use of chalk as a sinking agent was discouraged by many, but chalk was used because the ships were equipped to use it and the supplies were on hand.

6-29. The use of plaster as an absorbent material was tried on a coarse beach near Tregastel. Several other techniques using rubber absorbents, peat, and other fibrous materials were also tested.

6-30. Rocks that have been sprayed with dispersant are wind rowed in the lower intertidal zone. This was done in hope that the wave action associated with the incoming tide would wash the oil from the surface of the rocks.

6-31. Heavily oiled beach near l'Aber Wrac'h, 21 March 1978.

U.S. Government Printing Office: 1978-777-563 Region 8



Clam accumulation at high tide swash line at St. Michel-en-Grève on April 2, 1978