1979 Oil Spill Conference,
Amer. Petrol. Inst.,
Washington, D.C., p. 193-198

ROLE OF DYNAMIC COASTAL PROCESSES IN THE IMPACT AND DISPERSAL OF THE *AMOCO CADIZ* OIL SPILL (MARCH 1978) BRITTANY, FRANCE

Miles O. Hayes and Erich R. Gundlach
Coastal Research Division
Department of Geology
University of South Carolina
Columbia, South Carolina 29208

Laurent D'Ozouville
Centre National pour l'Exploitation des Oceans
Centre Oceanologique de Bretagne
Applied Geology
B.P.337
29273 Brest, France

ABSTRACT: *Between 60,000 and 65,000 tons of the* Amoco Cadiz *oil came ashore along approximately 70 km of the shoreline of Brittany during the first few weeks of the spill (March 16-30, 1978). 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 approximately 10,000 tons but by that time more than 300 km of shoreline had been contaminated.*

The details of oil erosion and burial were determined by resurveying 19 permanent beach profiles established during the first few days of the spill. These stations, plus an additional 147 beach observation stations, were revisited one month after the spill.

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.

Classification of the coastal environments of the Amoco Cadiz *oil spill site, according to an* 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. For example, exposed rocky coasts and wave-cut platforms (stations 1 and 2) were cleaned of extremely heavy doses of oil within a few days. Sheltered rocky coasts (station 8), sheltered tidal flats (station 9) and estuarine marsh systems (station 10) 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 United States threatened by potential oil spills. The Brittany coastline is particularly analogous to the coastline of Maine and parts of southern Alaska.*

The objectives of this paper are to describe briefly the influence of beach processes and sedimentation on the dispersal, grounding, burial and long-term fate of the oil spilled by the *Amoco Cadiz* along the shoreline of Brittany, France, in March-April 1978. 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 cleanup in the event of a major spill.

Field studies are still in progress at the spill site at the time of this writing (October 1978); therefore, the conclusions presented here should be considered tentative. The results given in this paper are based primarily on field studies carried out between March 19 and April 3 and April 20-28, 1978.

In the field, our work consisted of overflights and intensive ground inspection and surveys of the entire affected area. Field observations were conducted at 19 permanent beach survey stations and 147 beach observation stations (Figures 1 and 2).

Physical setting of spill site

Geological setting. 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, and metamorphic rocks. Inasmuch as the last major tectonism took place 200 million years B.P., the area now is tectonically stable. 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 systems. Everywhere, the primary shoreline trends are controlled by bedrock geology, with local trends being controlled by weathering and erosion along structural elements, such as faults, joints, and dikes.

Coastal processes. 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.

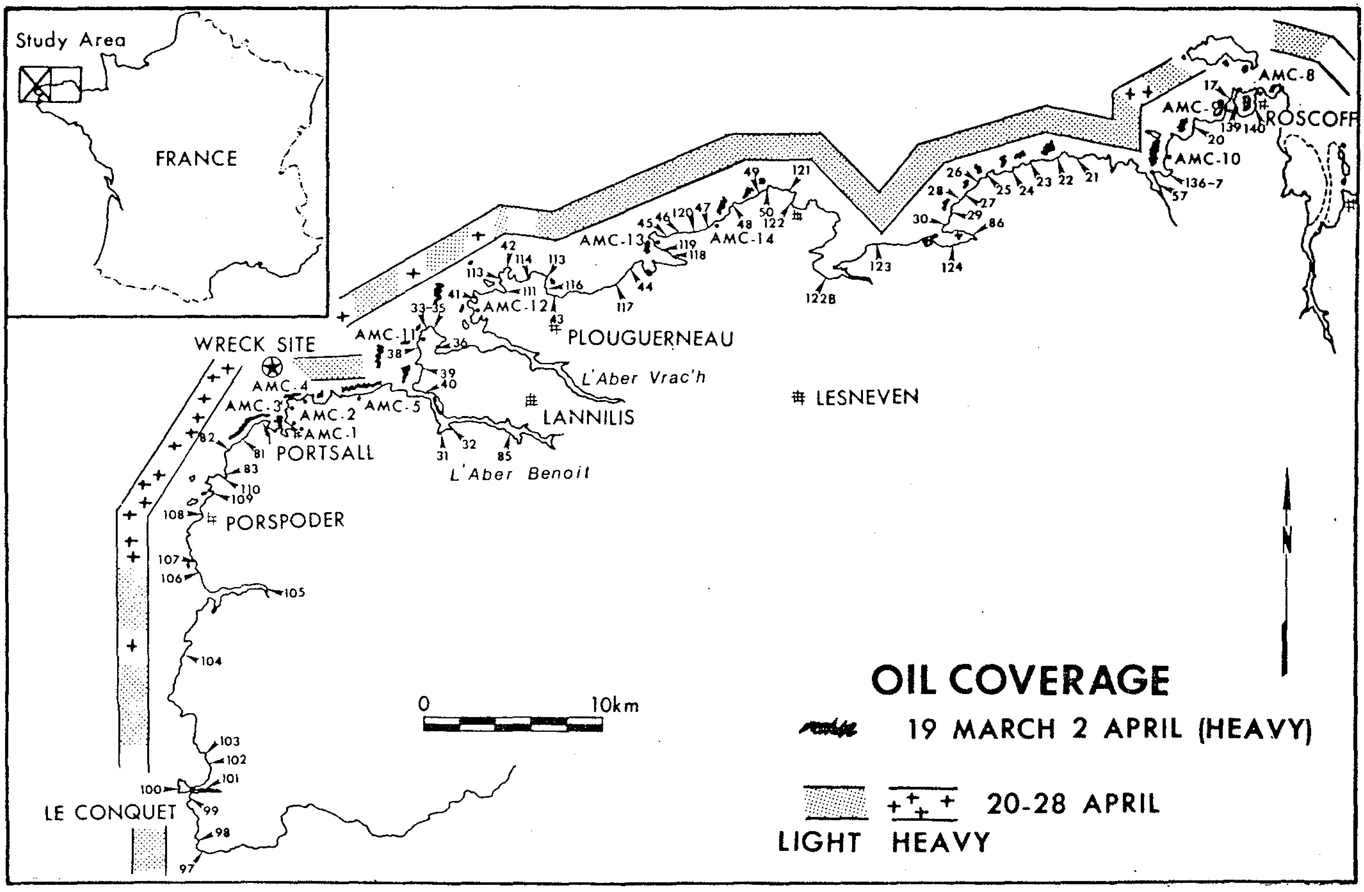

Figure 1. Locations of observation stations within western portion of the spill-affected area—Oil distributions for study periods one (March 19-April 2) and two (April 20-28) are indicated; numbers indicate field study sites.

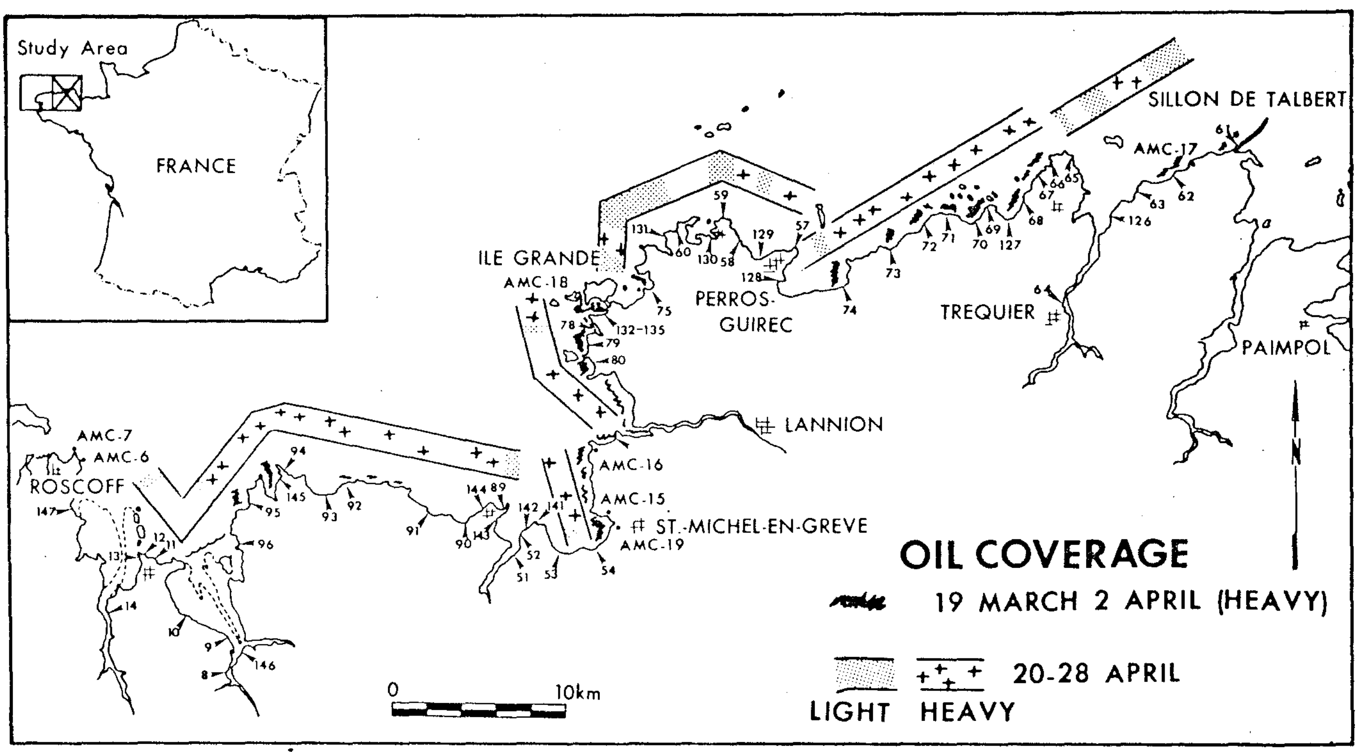

Figure 2. Observation stations within eastern portion of the spill-affected area—Oil distribution is indicated.

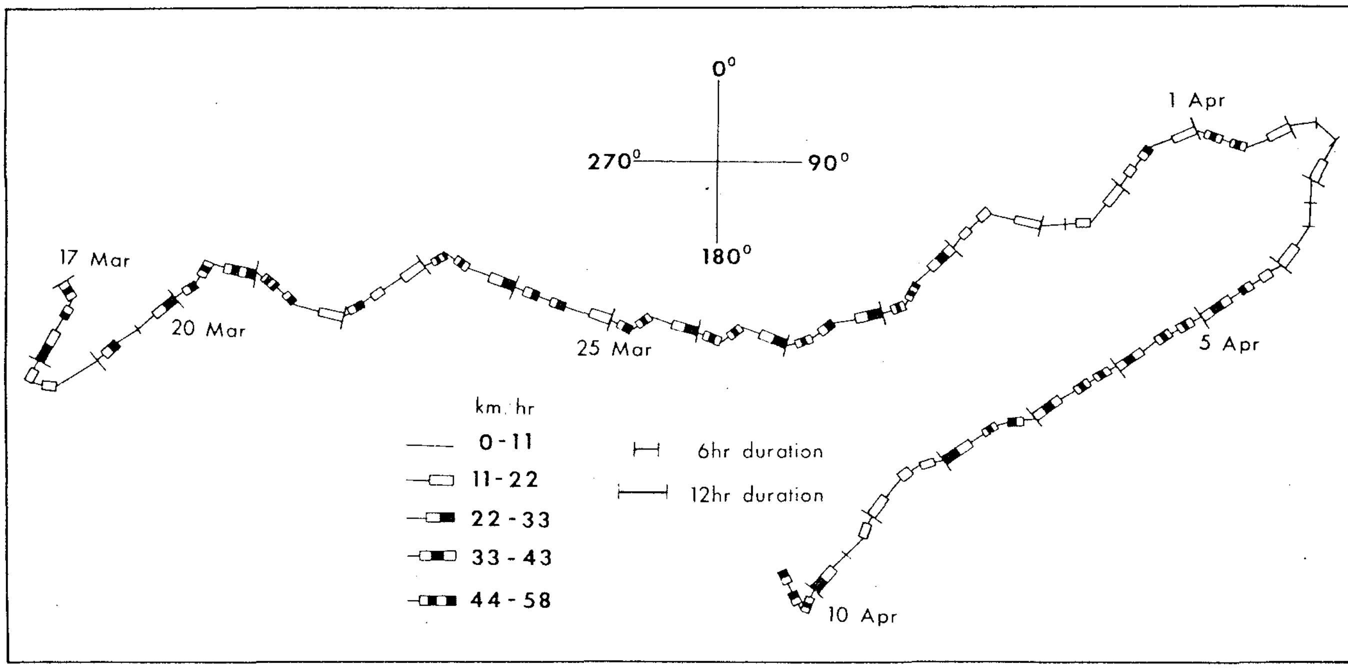

Figure 3. Wind pattern for March 17-April 10 from the French meteorological station 1 km north of l'Aber Wrac'h— The wind shift on April 2 caused the oiling of previously clean coastal areas south of the wreck site.

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 (Figure 3) 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 of more than 20 km/hr were common 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, these and later northeast winds, aided by tidal currents, dispersed the oil to the west and south during early April. Wind measurements that we made in the field April 22-26 showed variable results, but easterly winds predominated.

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.

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. These large tides generated strong tidal currents throughout the spill site. 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 such as 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. 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.

Coastal morphology. The portion of the Brittany coast impacted by *Amoco Cadiz* is an irregular, low-lying ria coastline, which is composed mainly of small drowned river valleys and protruding rocky headlands. A recent publication by Chasse[1] describes the morphology and sediments of selected segments of the spill site in great detail.

Depositional beaches are rare on the Brittany coast. Where present, they consist of sheltered pocket beaches, crenulate bays and tombolos. 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.

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.

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. Intermediate-sized, well-rounded cobbles (20 to 40 cm in diameter) make up some beaches exposed to high wave action. In more sheltered areas, gravel beach ridges similar to those of New England and Alaska have accumulated. In places, moderately-sorted gravel accumulations occur as a high tide rim around intertidal sand flats. Thin gravel veneers overlie clay and peat substrates on some of the erosional beaches.

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

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. Swash lines of dead razor clams and heart urchins were accumulated along the beach at St. Michel-en-Greve on April 2.

Muddy sediments are rare in the spill site, presumably because of the high wave and current energy conditions that prevail. Some of the rias contain muddy flats in their upper reaches, and the salt marshes usually contain muddy sediments.

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, we applied a modified version of the zonal method to the *Amoco Cadiz* oil spill site.

The zonal method. The zonal method was developed by Hayes and associates[5] 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,[7] and during studies of the *Metula, Urquiola,* and *Jakob Maersk* oil spills.[3] 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 the National Oceanic and Atmospheric Administration's Outer Continental Shelf Environmental Assessment Program. In a study of lower Cook Inlet (for the State of Alaska), a total of 1,216 km of coast was classified within 21 days by a team of three persons.[6] A similar approach was taken during our study of the *Amoco Cadiz* oil spill.

Flights. Extensive aerial photography and tape descriptions were carried out during five flights over the *Amoco Cadiz* spill site. 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.

Beach stations. A total of 166 beach stations was visited (Figures 1 and 2). Stations of two types were established, F-stations (plain numbers) and AMC-stations (numbers preceded by AMC). At the 147 F-stations, the site was visually inspected, photographs taken, and observations recorded on tape. Work at the 19 AMC-stations included the following:

1. A topographic profile of the beach (at low tide). The profile is measured by the horizon-leveling technique of Emery.[2] 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. An example of a measured beach profile is illustrated in Figure 4, and an example of a repeated station is given in Figure 5.
2. Three equally-spaced sediment samples. 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 in the laboratory.
3. Trenches to determine the distribution of buried oil. Each trench was sketched and photographed in detail.
4. A sketch to show the general coastal geomorphology and the surficial oil distribution. An example of a field sketch is given in Figure 4.
5. Photographs of all aspects of the beach.

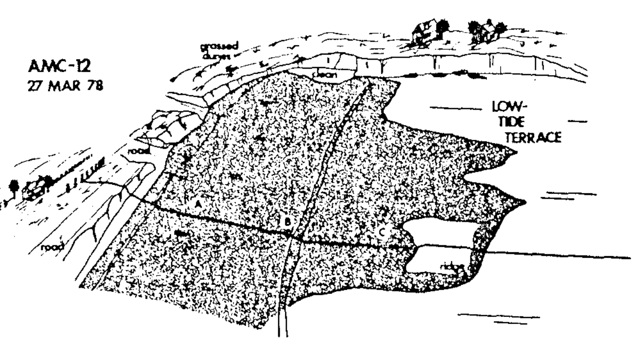

Figure 4. Topographic profile and oil coverage at station AMC-12 on March 27—The thickness of the oil coverage line is proportional to actual oil thickness; heaviest accumulations occurred on the low-tide terrace in a low-relief runnel behind a ridge.

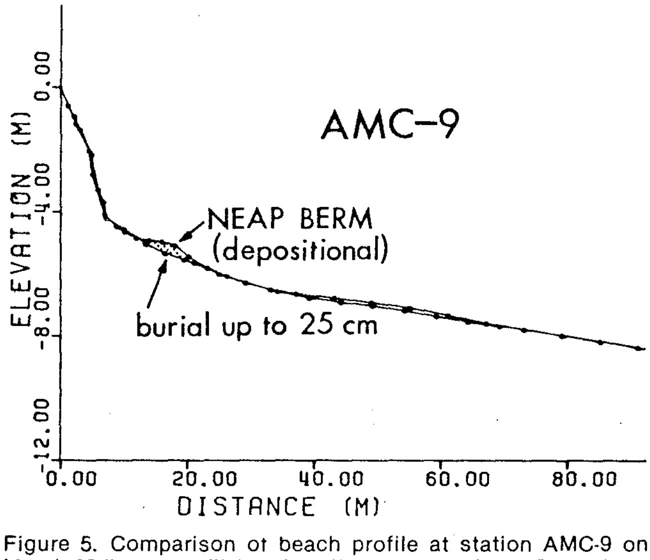

Figure 5. Comparison of beach profile at station AMC-9 on March 25 (lower profile) and April 1 (upper profile)—Deposition of a neap berm during the intervening six days buried oil up to 25 cm in depth.

Oil distribution. The occurrence of oil along the shoreline was mapped 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 1 and 2.

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 also was 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 percent of this volume was mousse. The 10 percent value was derived from analyses by Anne Blount (of our group) on more than 50 oiled sediment samples from the *Metula* site. All mousse was assumed to be 60 percent 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 then was measured on 1:25,000 scale topographic maps and multiplied by this value. This was done for both study periods (March 19-April 2 and April 20-28) to determine the net change.

Preliminary conclusions

Details of the oil impact along the whole coastline were presented in the NOAA/Environmental Protection Agency special report issued in April 1978.[4] At the end of our second site visit on April 28, significant quantities of oil remained in the water and on the shoreline at 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.

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; those facing east, particularly those within the larger embayments, were mostly unaffected. 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 (Figure 3), the oil was spread far into 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.

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 one 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-Tregastel (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 versus 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 sediments 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 crenulate bays; tombolos; low-tide terrace, ridge-and-runnel systems; scour pits around boulders; and regional bedding and joint patterns in the bedrock.

Where crenulate bays occur on west-facing shorelines, they tended to trap oil at the head of the bay (northeast end), where the shoreline has its maximum curvature. The tail or southwest portion usually was free of oil during the first days of the spill (when winds were westerly).

Another morphological feature, the tombolo, also had a marked influence on the initial deposition of oil. Oil became trapped behind rocks or a small island on the tombolo because of the convergence of wave fronts around the offshore rocks.

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 (Figure 5). 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 percent 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.

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.[3,6] The index is based mostly on predicted longevity of oil within each environment, but 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. Table 1 presents a summary of our observations regarding the vulnerability index at the *Amoco Cadiz* spill site.

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 rating high on the scale generally remained more highly oiled at the end of April (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 (such as the Alaska coast) seems to be clearly justified.

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 the tidal 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 sunk. Therefore, this process, (Figure 6) is possibly a significant factor in aiding the oil to sink to the bottom.

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

Table 1. The oil spill vulnerability index[3,6] with particular reference to the *Amoco Cadiz* oil spill—Higher index values indicate greater long-term damage by the spill.

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 cleanup needed
2	Eroding wave-cut platforms; south of Portsall and F-1 to F-82 10 days	Exposed to high wave energy; initial oiling removed within 10 days
3	Fine-grained sand beaches; stations south of Roscoff (AMC-9 and 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) and 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 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; cleanup 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; cleanup 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; cleanup activities removed major oil accumulations but left remaining oil deeply churned into the sediment; biological recovery 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; cleanup activities removed the thick oil accumulations but also trampled much of the area; biological recovery yet to be determined

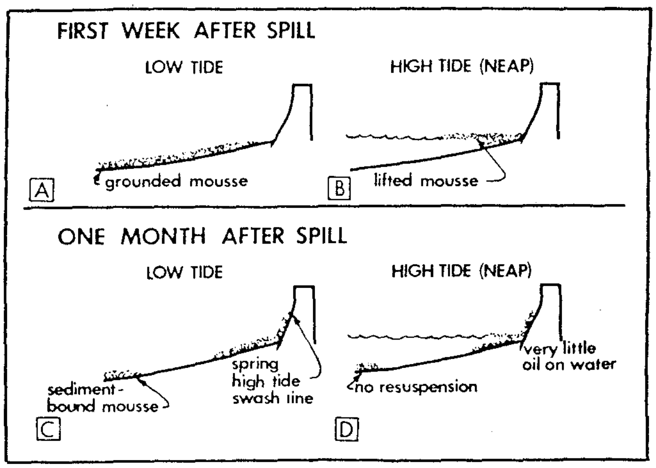

Figure 6. Observation of oil response at Portsall—During the first week after the spill, most of the oil lifted off the surface of the sand flat with every incoming tide; during our second survey, mousse mixed with the sediment remained on the sand flat and beachface even as the tide flooded; only a light oil sheen was visible on the surface of the water.

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.

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 had an obvious oil sheen and often had visible droplets of mousse. If the concentration of oil in the ground water reaches lethal proportions, 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 employed to clean up the beach undoubtedly intensified 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 saw at St. Michel-en-Greve, can only increase the contamination. Follow-up studies of beach processes and water chemistry are needed for a better understanding of this problem.

Oil dispersal. During the first two weeks of the oil spill, a total of 72 km of coast was heavily oiled. Using our estimated quantity of 886.5 tons of oil per kilometer of shoreline (for details of method of calculation, see Gundlach and Hayes[4]) 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 heavy oiled. Using our oil estimates for session two, we can account for 10,310 metric tons of oil (a loss of 84 percent 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. 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 breakdown and dispersion of the large oil masses by waves and currents and to a major shift in wind direction (from westerlies to easterlies).

Acknowledgments

The primary purpose of our work on the *Amoco Cadiz* spill was to provide assistance to the NOAA spilled oil research (SOR) team 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 NOAA Environmental Research Laboratories. 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 profited from helpful discussions with Roy Hann of Texas A&M University. Living facilities, a stimulating scientific environment, and miscellaneous logistical support were provided by the Centre National pour l'Exploitation des Oceans, Centre Oceanologique de Bretagne.

References

1. Chasse, Claude J. M., 1972. Economie sedimentaire et biologique (production) des estrans meubles des cotes de Bretagne. Thesis, l'Universite de Paris VI. 293p
2. Emery, K. O., 1961. A simple method of measuring beach profiles. *Limnology and Oceanography.* v6, pp90-93
3. Gundlach, E. R., and M. O. Hayes, 1978. Vulnerability of coastal environments to oil spill impacts. *Marine Technology Society Journal.* v12, n4, pp18-27
4. Gundlach, E. R., and M. O. Hayes, April 1978. Investigation of beach processes. in *NOAA/EPA Special Report, The* Amoco Cadiz *Oil Spill,* Wilmot N. Hess (ed). pp85-196
5. 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). Proceedings of the Third Annual Geomorphology Symposium, Binghamton, New York. pp11-41
6. Hayes, M. O., P. J. Brown, and J. Michel, 1976. Coastal Morphology and Sedimentation, Lower Cook Inlet, Alaska: With Emphasis on Potential Oil Spill Impacts. Technical Report No. 12-CRD. Coastal Research Division, Department of Geology, University of South Carolina. 107p
7. Hayes, M. O., C. H. Ruby, M. F. Stephen and S. J. Wilson, 1976. Geomorphology of the southern coast of Alaska. 15th Conference on Coastal Engineering Processes. v2, pp1992-2008