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E. R. Gundlach,[1] *M. O. Hayes,*[1] *C. H. Ruby,*[1] *L. G. Ward,*[1]
A. E. Blount,[1] *I. A. Fischer,*[1] *and R. J. Stein*[1]

Some Guidelines for Oil-Spill Control in Coastal Environments, Based on Field Studies of Four Oil Spills

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ABSTRACT: It is essential to understand the factors influencing the distribution, damage and long-term persistence of oil spills in order to adequately plan for, and apply appropriate cleanup techniques. Based on the study of two massive spills [*Metula*, 47 700 t (53 000 tons)]; [*Urquiola*, 22 500 to 27 000 t (25 000 to 30 000 tons)] and two smaller spills under ice conditions [*Bouchard 65*, 248 t (276 tons); *Ethel H.*, 1350 t (1500 tons)], these factors are (1) wind stress and water currents, (2) beach activity and grain size, (3) tidal stage, (4) wave energy, (5) oil quantity and composition, and (6) ice effects, where applicable.

Coastal environments vary significantly in terms of resultant damage from spilled oil. Subsequent cleanup by dispersants or mechanical means should be planned accordingly. Considering the aforementioned factors, as well as initial biological effects, a classification of coastal environments in terms of potential oil spill damage has been developed. In order of increasing vulnerability, these environments are: (1) exposed, steeply dipping or cliffed rocky shores; (2) eroding wave-cut platforms; (3) fine-sand beaches; (4) coarse-sand beaches; (5) exposed, compacted tidal flats; (6) mixed sand and gravel beaches; (7) gravel beaches; (8) sheltered rocky coasts; (9) sheltered tidal flats; and (10) salt marshes and mangroves. This classification can be used to delineate oil-sensitive environments as part of an overall contingency plan to limit damage during an oil spill.

KEY WORDS: oil spills, coastal environments, marine and beach processes, cleanup

An understanding of the physical processes and shoreline characteristics influencing the distribution and effects of spilled oil is essential in

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[1] Coastal Research Division, Geology Department, University of South Carolina, Columbia, S. C. 29208.

planning appropriate mechanical or chemical cleanup operations. Based on observation of two massive spills, and two minor spills under ice conditions, a discussion of the primary influencing factors is presented. In addition, the delineation of coastal environments particularly sensitive to oil contaminants is an important aspect of planning against spill damage. To this end, a Vulnerability Index classifying shoreline environments in order of potential damage from oil spills has been developed. Vulnerability is based on shoreline interaction with spilled oil, long-term oil persistence, and initial biological effects. This report concentrates on oil impact within coastal environments, the most biologically productive of all marine areas [*1,2*].[2] In addition, 75 percent of all oil discharges in the United States and 78 percent of worldwide tanker spills occur within coastal waters [*3,4*].

These investigations were carried out by the University of South Carolina, Oil Spill Assessment Team (OSAT) under the support of the National Science Foundation. Information used in this report was derived essentially from study of the *Metula*, *Urquiola*, *Bouchard 65* and *Ethel H.* oil spills. A brief synopsis of each spill incident follows.

Metula oil spill—On 9 August 1974, the VLCC *Metula* [185 400 t (206,000 tons deadweight) (dwt)] grounded and ruptured its forward tanks while passing through the Strait of Magellan, Chile. Over the next four weeks, 45 900 t (51 000 tons) of Saudi Arabian crude oil and 1800 t (2000 tons) of Bunker C escaped to the surrounding waters. Spread by strong winds and tidal currents, an estimated 36 000 t (40000 tons) of oil impacted approximately 250 km (150 miles) of shoreline [5-8]. Figure 1(*a*) shows the overall distribution of oil in the area 1½ years after impact. Biological damage was severe, killing 3000 to 4000 birds as well as mussels and nekton. Fortunately, nearby penguin rookeries entirely escaped damage [*9*]. Because no cleanup was attempted, the *Metula* spill provided an excellent opportunity to monitor the long-term perseverance of oil within this environment.

Urquiola oil spill—The *Urquiola* grounded, exploded, and burned at the entrance to La Coruña harbor (Spain) on 12 May 1976. In total, 90 000 t (100 000 tons) of its 96 300 t (107 000) ton cargo of Persian Gulf crude oil was lost [*10,11*]. Over the next few weeks, approximately 22 500 to 27 000 t (25 000 to 30 000 tons) of oil washed onto the shoreline. By 1 June, 215 km (129 miles) were oiled, of which 60 km (36 miles) received moderate to heavy accumulations [Fig. 1(*b*)]. Ecological damage was severe, killing 70 percent of the edible cockle (*Cerastoderma edule*) in some areas and 10 to 30 percent of other species of clams [*10,12*]. At least 1800 t (2000 tons) of dispersants of various trademarks were used to treat the oil around the ship and on one beach [*11*]. Other cleanup efforts were very limited.

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

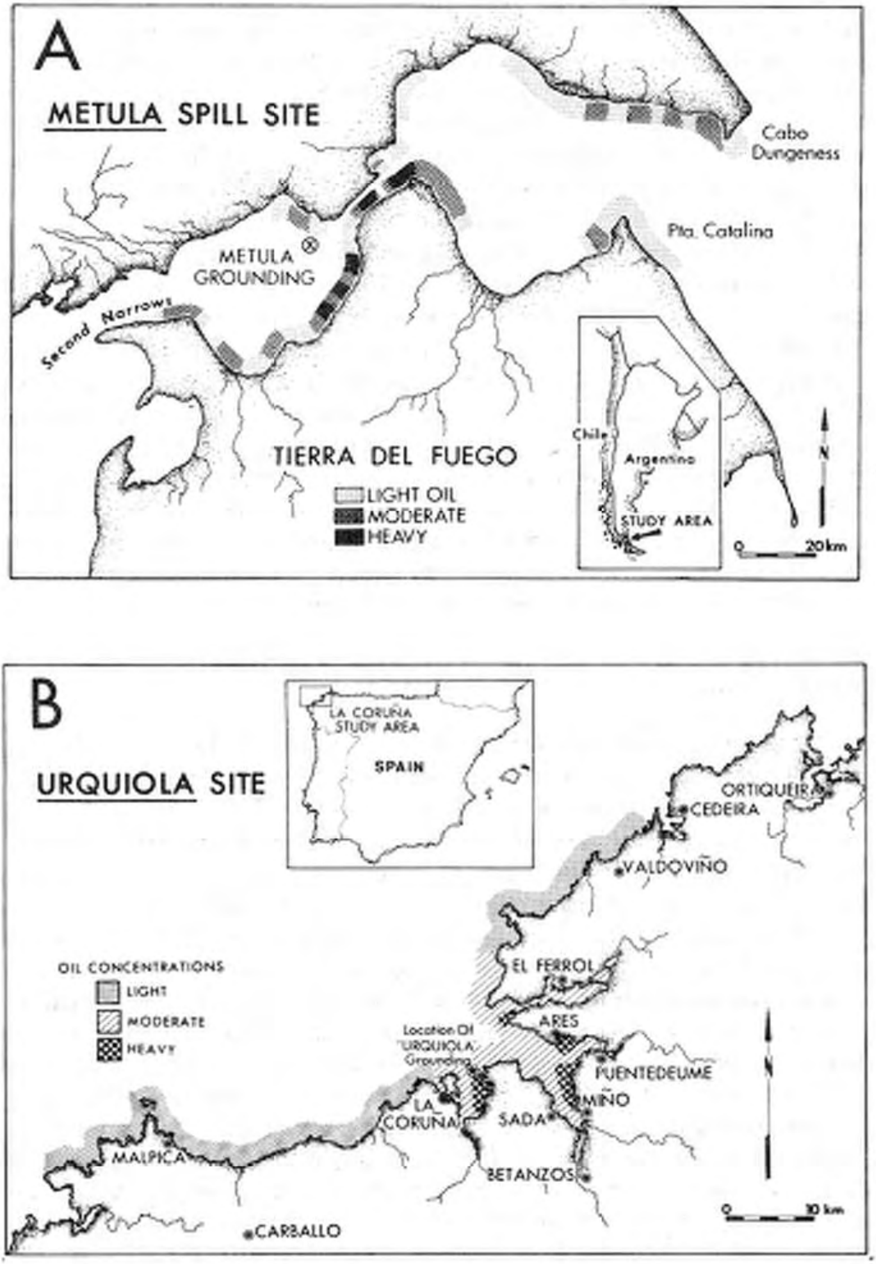

FIG. 1—*Location and distribution of oil at* (A) *the* Metula *spill site, 18 months after the spill, and* (B) *the* Urquiola *spill site, 19 days after the spill.*

Bouchard 65—The Barge *Bouchard 65*, carrying 118 million litres (31 million gallons) of No. 2 fuel oil, ran aground in the northeast section of Buzzards Bay, Massachusetts, on 28 January 1977. As a result, 308 000 litres (81 000 gal) of its cargo was lost. The heavy ice cover in Buzzards Bay at that time rendered normal open-water cleanup techniques generally ineffective [*13*]. Use of land-based suction trucks and burning were the only methods which proved successful. Only 12 percent of the spilled oil was recovered or burned. Much of the remaining oil, intermixed with the bay ice, was released during a melting period two weeks after the original spill. In a number of instances, ice acted to protect the beaches from oil contamination. Biological surveys have, as yet, been inconclusive.

Ethel H.—The barge *Ethel H.*, carrying 9.5 million litres (2.5 million gallons) of No. 6 fuel oil ran aground in the Hudson River just south of West Point on 4 February 1977. Over the next few days, a total of about 2 million litres (520 000 gal) was spilled. At the time of the incident, the Hudson River was covered by river ice and shorefast ice. Most of the spilled oil was mixed with the moving river ice and ultimately moved downriver and out to sea. Shorefast ice protected most of the river shoreline. Biological damage seemingly was very slight. Once again, standard cleanup techniques used for open-water spills proved ineffective.

Method of Study

The geomorphology, sedimentation, and oil distribution of the *Metula* and *Urquiola* spill sites were studied in detail by application of a rapid reconnaissance technique called the *zonal method* [*14*]. The first phase of the zonal study encompasses collection of all relevant data on the spill area (including charts, aerial photographs, tide tables, and previous literature) and an aerial survey to determine the extent of the spill and the interval for ground stations. The quantity of ground stations varied with each study site, depending on local geomorphology and oil distribution. Table 1 presents the study periods and station information for each investigation. At each station, a topographic profile of the entire intertidal zone was run during low tide. Observations and sketches were made of the following: (1) oil distribution and quantity, (2) sedimentary characteristics, (3) marine and meteorologic conditions, (4) depth of oil burial and penetration, and (5) all relevant geomorphic features. Each study site was photographed in detail. Sediment samples were taken from at least three equidistant locations along the beach profile and were later analyzed for size and statistical characteristics [17]. Maps were constructed of particular representative sites indicating oil distribution on the surface and at depth. In the iced areas of the *Bouchard 65* and *Ethel H.* oil spills, detailed observations were made of oil-ice interaction and methods of cleanup.

TABLE 1—*Summary of study periods, station, and interval for each field investigation.*

Metula Spill Study:	
12–20 Aug. 75:	initial reconnaissance of the spill site; 19 stations monitored [*8*]
4 Feb.–13 Mar. 76:	study of 66 stations, each located 3 km apart. In addition, 16 representative areas were studied in great detail. Of these, 12 were remonitored to determine short-term changes in beach morphology [*15*]
12 Aug.–23 Aug. 76:	follow-up study. Continued analyses of 12 stations monitored previously [*15*]
Urquiola Spill Study:	
17 May–10 June 76:	detailed analysis of 32 stations, one at each major oil-affected environment. In addition, 67 other stations were visually examined for oil distribution and quantity [*16*]
2 June–10 June 76:	Detailed study of four oil-affected wetlands areas [*12*].
Bouchard 65 Spill Study:	
31 Jan.–3 Feb. 77:	aerial and ground surveys of affected shoreline and ice areas. Detailed analysis of cleanup techniques used on the ice [*13*]
3 June–5 June 77:	revisit of spill site. Analysis of affected shoreline and remeasurement of beach profiles
Ethyl H. Spill Study:	aerial and surface observations of affected shorelines and ice areas. Analysis of cleanup techniques used on the ice. Tracking of oil concentrations downriver

Results

Factors Influencing Oil Distribution and Persistence

The combined study of all four oil spills enabled observations of oil impact on a wide variety of shoreline types. Table 2 lists these environments and geomorphically similar areas in the United States. The distribution and persistence of oil pollution within each environment was controlled by a complex interaction among the following factors: (1) wind stress and water currents, (2) beach activity and grain size, (3) tidal stage, (4) wave energy, (5) oil quantity and composition, and (6) ice effects where applicable. A discussion of each factor follows.

Wind Stress and Water Currents—The movement of oil on water is controlled by winds and surface currents. Studies indicate that winds transport oil at roughly 3 percent of wind speed, although this may vary during actual spills [*18*]. Wind stress was particularly important in controlling oil distribution during the *Metula* and *Urquiola* spills. Strong westerly winds up to 100 km/h (60 mph) at the time of the *Metula* spill forced much of the oil onto the southeastern shore of the Strait of Magellan [see Fig. 1(*a*)]. At the *Urquiola* site, an additional 40 km (24 miles) of coast was contaminated due to a shift in wind direction and

TABLE 2—*Characteristics of each spill site and geomorphically similar areas within the United States. In the case of the* Metula *spill, the climate (semi-arid) is different from that of the presented U.S. analogues. Accordingly, a minor decrease in projected spill persistence may occur as a result of wetter U.S. climates.*

Oil Spill	Characteristics of Spill Site		Affected Shoreline Types	Geomorphic U.S. Analogues
	Climate	Tidal Range		
Metula	semi-arid, cold	two areas: 4 to 7 m 7 to 10 m	mixed sand and gravel beaches; eroding wave-cut terraces; exposed and sheltered tidal flats, marshes	New England, Long Island, Pacific Coast (especially Alaska)
Urquiola	temperate	2 to 4 m	fine-sand, coarse-sand and gravel beaches; sheltered and exposed rocky coasts; tidal flats and marshes	northern New England, southeast Atlantic Coast
Bouchard 65 and *Ethel H.*	ice conditions, temperate, midwinter	1 to 3 m	shorefast and float ice; small areas of sand and gravel beaches	ice-prone areas, particularly New England and Alaska

velocity two weeks after the grounding. Surface currents have the capability of moving oil at greater speeds than wind stress alone (a 100-knot wind would move oil at only 3 knots.). Currents may be caused by either tidal action or alongshore drift. In embayments and narrow channels, currents can be exceptionally strong (8 knots in the Strait of Magellan, 4 knots in Spain). Actual oil transport during a spill is exceedingly complex and difficult to predict. Changes in (1) wind direction, velocity, and duration, (2) surface water currents, and (3) time of major oil release, all cause variation in the drift pattern of the spill.

Beach Activity and Grain Size—Beach activity refers to the erosional or depositional phase of shoreline development. Two types of activity are possible: events associated with the beach cycle and events connected with erosion or deposition caused by alongshore sediment transport. The beach cycle is a repetitive construction-destruction of the beach in response to waves and tides [*19*]. Flat, long-period waves generally move material onto the beach, while steeper, high-frequency waves (as during storms) do the opposite. Beach response to tidal cycles is shown by sediment accretion or beach construction as the tide progresses from neap to spring conditions. Oil can be rapidly buried during the constructional stage in beach development, making cleanup increasingly more difficult. A diagrammatic example of this process is presented in Fig. 2. In addition to the beach cycle, oil may be buried by alongshore depositonal-erosional patterns as indicated in Fig. 3. In coastal areas subject to extensive erosion, deposited oil would soon be removed by natural processes, making a large cleanup operation unnecessary.

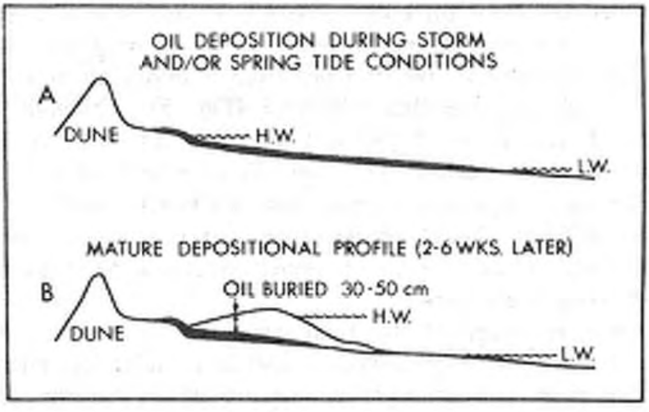

FIG. 2—*Process of oil burial during spring tides or storm conditions. Cleanup becomes increasingly more difficult as depth of burial increases.*

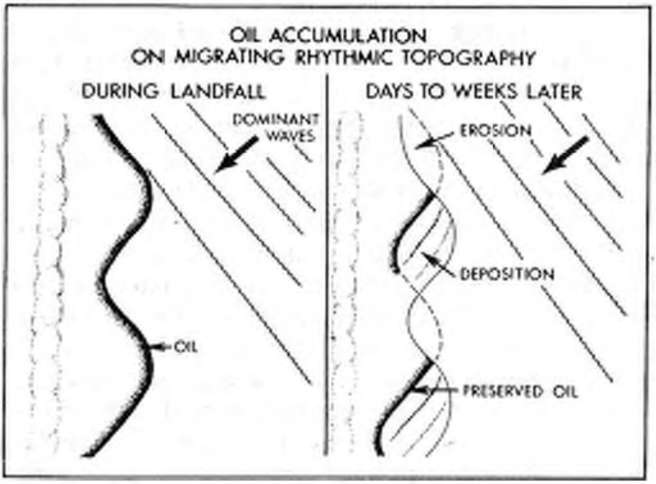

FIG. 3—*Process by which oil can be buried or eroded by changes in beach morphology due to alongshore erosional-depositional patterns.*

The sedimentary characteristics of a spill-affected beach are also important considerations. Grain size influences the depth of oil burial by accreting sediment (larger grains are more easily transported by waves) and the thickness of oiled sediment. Oiled sediment, visible as distinct layers within the beach, is caused by oil sinking by gravity into the beach and by the mixing of oncoming oil and sediment by wave action. Figure 4 shows the depth of oil burial and thickness of oiled sediment as a function of grain size as measured at most of the oil-affected beaches in Spain. Both oil burial and oiled sediment thickness generally increased as the grain size coarsened. On fine-sand beaches, oil penetration was limited to the upper few centimeters. Representative trenches from a find-sand and a coarse-sand beach clearly indicate this difference (Fig. 5). Although not sufficiently studied, the use of dispersants does not appear to be advantageous for most oiled beaches. The emulsifying action of the chemical agents enables oil to penetrate further into the beach, making complete cleanup more difficult [*20,21*]. However, further research is necessary to document the actual increase in oil penetration due to dispersants on beaches of differing grain sizes.

Tidal Stage—The stage of the tidal cycle is important in terms of the beach cycle (as previously discussed) and as a major influence on the surficial distribution and ultimate persistence of oil on the shoreline. During both the *Metula* and *Urquiola* spills, extensive oil accumulations washed ashore during spring tides (Fig. 6). At this time, oil was pushed by waves to the high-tide swashline along the highest portion of the beach.

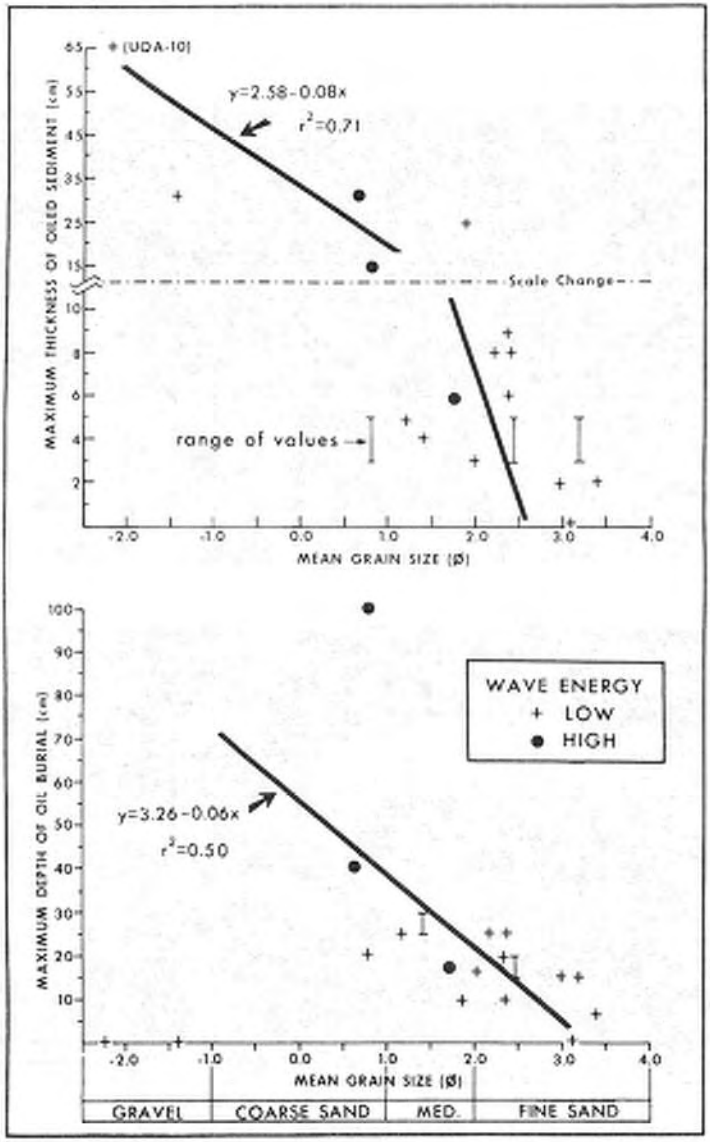

FIG. 4—*Thickness of oiled sediments* (top) *and depth of oil burial* (bottom) *as a function of grain size, measured from most major oil-impacted beaches at the* Urquiola *spill site. The regression line and correlation coefficient* (r^2) *are indicated on each graph* (n = *18*, top; n = *15*, bottom). *Generally, as the grain size increases, so does the thickness of oiled sediment and depth of oil burial.*

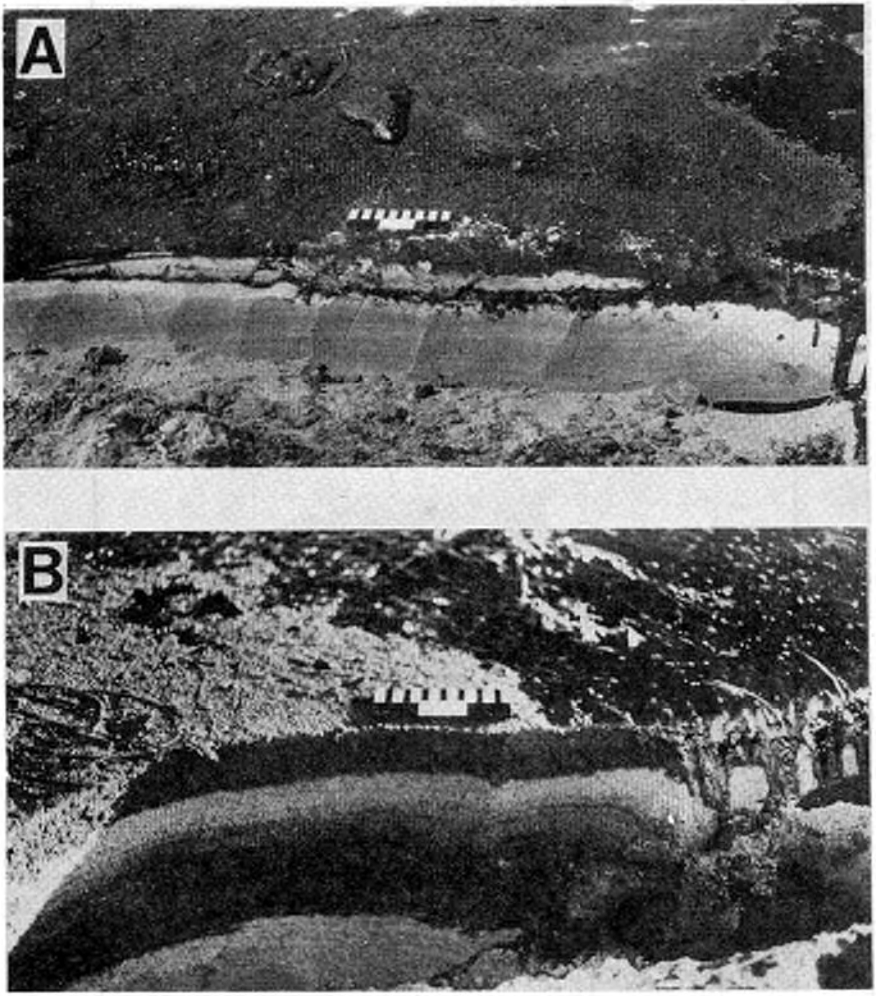

FIG. 5—*Trenches through the berm and berm-runnel sections of beach containing* (A) *fine sand* ($M_z = 0.11 mm$) *and* (B) *coarse sand* ($M_z = 0.56 mm$). *The pictured scale is 15 cm. Water in both cases is to the left. Oil burial and penetration is significantly greater on coarse-sand beaches.*

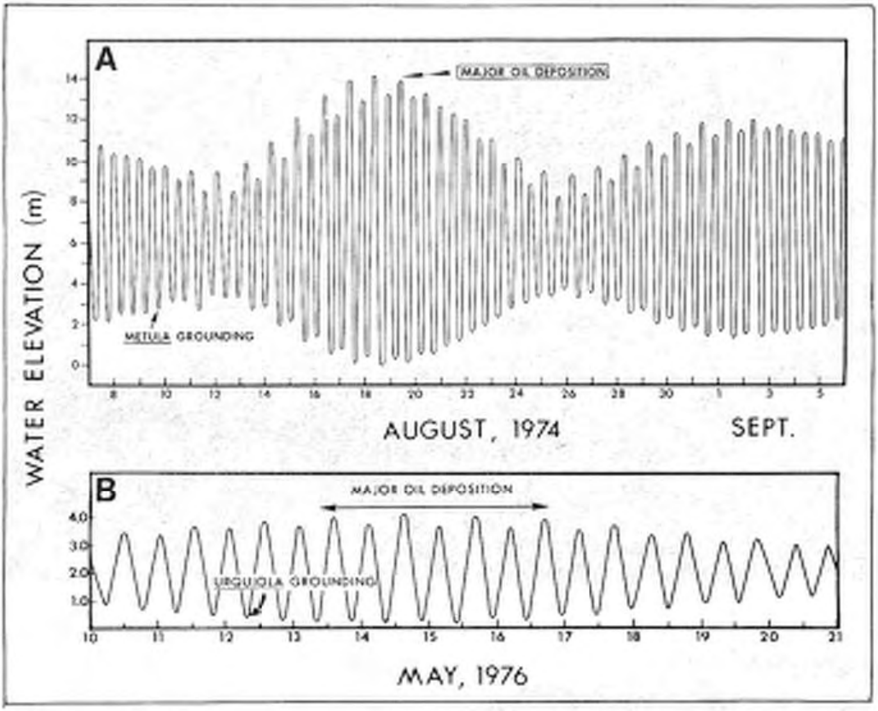

FIG. 6—*Tide curves during the* (A) Metula *oil spill and the* (B) Urquiola *oil spill. Source* [22, 23]. *In both cases, oil came ashore during spring high tides, forming thick oil layers along the highest portions of the beach. Oil deposited along the high-tide swash area during the* Metula *spill remained essentially unaffected by wave activity for at least two years after the spill (see Fig. 7).*

As the tidal cycle returned to neap, the already deposited oil remained above significant wave or swash activity. The high tidal level which occurred during the *Metula* spill apparently was not duplicated for at least two years after the spill. Oil deposited along the spring high-tide swashline of mixed sand and gravel beaches remained basically in the same form and condition throughout our study (Fig. 7). In summary, oil coming onshore as the tide is going toward spring conditions is particularly hazardous since it has a high potential for burial at the berm crest by beach accretion and deposition above major (erosive) wave activity.

Wave Energy—Examples from Chile and Spain indicate that the action of waves on the shoreline is an extremely influential process during and after oil impact. During both spills, oil was quickly eliminated from zones exposed to direct wave attack. Most Chilean beaches showed oil remaining only on the highest and lowest portions of the beach, areas of limited wave activity (Figs. 7 and 8). In Spain, cliffed rocky headlands subject to high

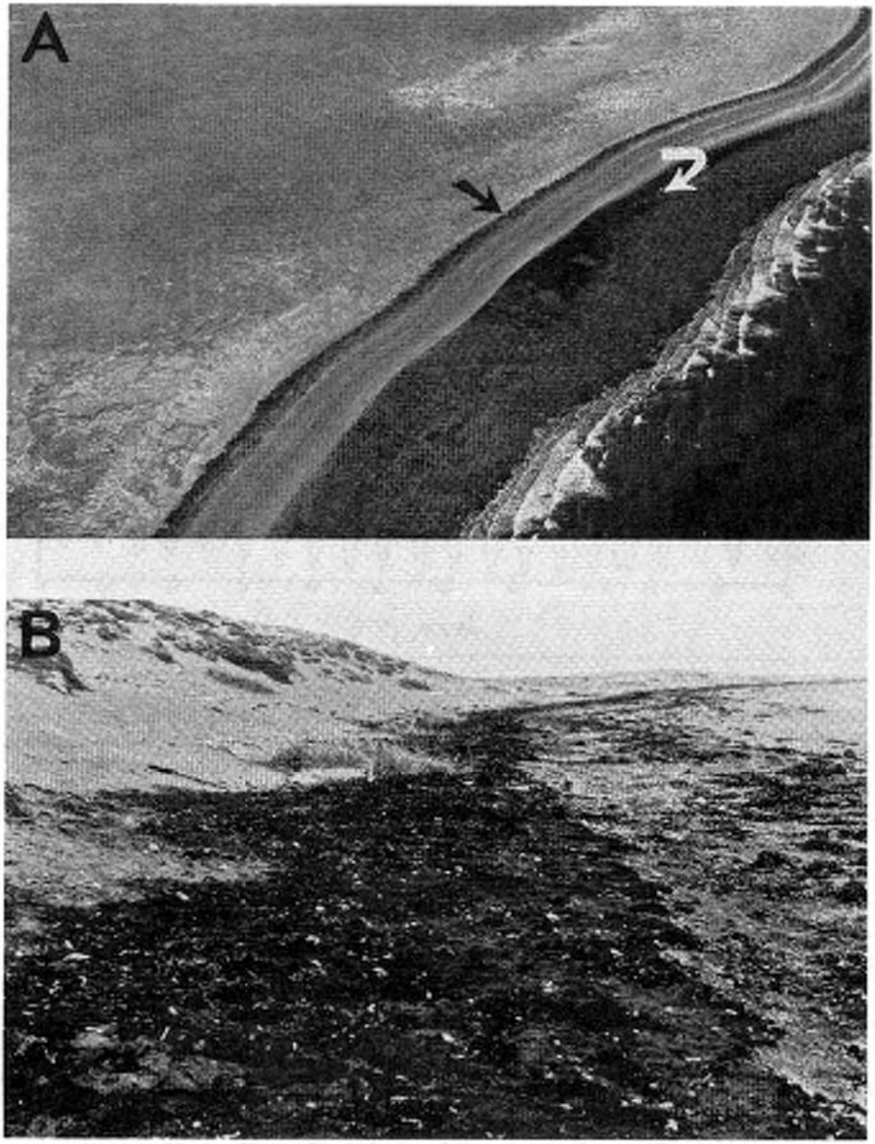

FIG. 7—(A) *Arrows indicate oil deposits on mixed sand and gravel beaches on the south side of the Strait of Magellan (also see Fig. 8). Black arrow indicates band of oil visible in bottom photograph.* (B) *Ground level photograph, taken 1½ years after the* Metula *spill, illustrating oil deposited during spring high-tide conditions.*

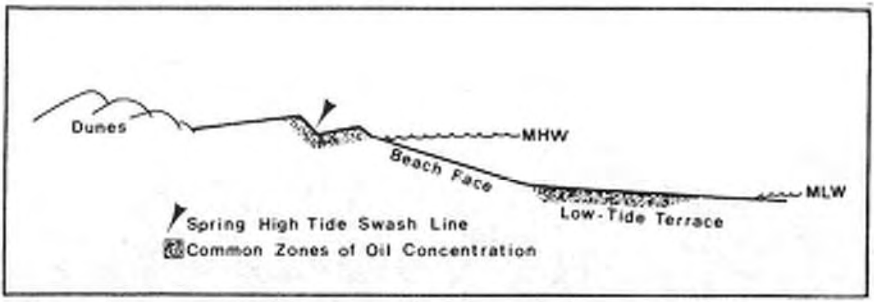

FIG. 8—*Zones of oil persistence in the Strait of Magellan. Oil is rapidly eliminated from the beachface by wave activity.*

wave energies showed little to no environmental damage. Oil was held offshore by wave reflection and rarely came in direct contact with the shoreline. In contrast, areas sheltered from wave action, including rocky coves, tidal flats, and marshes, received very heavy oil accumulations and exhibited the greatest environmental damage. Similarly, in Chile both a marsh and a tidal flat received extensive and long-lasting oil deposits. Two years later, these areas still appeared highly damaged (Fig. 9).

Oil Quantity and Composition—The quantity of oil spilled influences the possible total extent of affected shoreline, the distribution of oil on the beach, and the duration for which oil-shoreline interactions (such as burial and mixing) can be maintained. As indicated by the *Metula* and *Urquiola* case studies, massive spills have the capability of affecting large sections of coastline, 150 and 215 km (90 and 129 miles), respectively. Once oil impacts the shoreline, the quantity of oil available determines its surficial distribution on beaches. At low quantities, oil is deposited primarily along the high-tide swashline. As the quantity increases, oil increasingly covers the rest of the beach face. Under heavy accumulations, the entire intertidal zone becomes covered, but with thicker concentrations forming along the high-tide swashline. The extent of oil burial and the thickness of oiled sediment is also partially dependent on the duration for which oil remains in the water. Greater penetration and deeper burial occur with higher oil quantities.

The chemical properties of petroleum vary greatly among crude oils and processed oils. The boiling point, specific gravity or density, and viscosity are the major factors influencing evaporation rates, solubility, and dispersion [*18*]. Oils having a low boiling point will evaporate rapidly upon exposure to the atmosphere, greatly reducing the remaining volume of oil. Denser, more viscous oils such as Bunker C and California crude will evaporate and disperse much less readily. The viscosity of the oil also

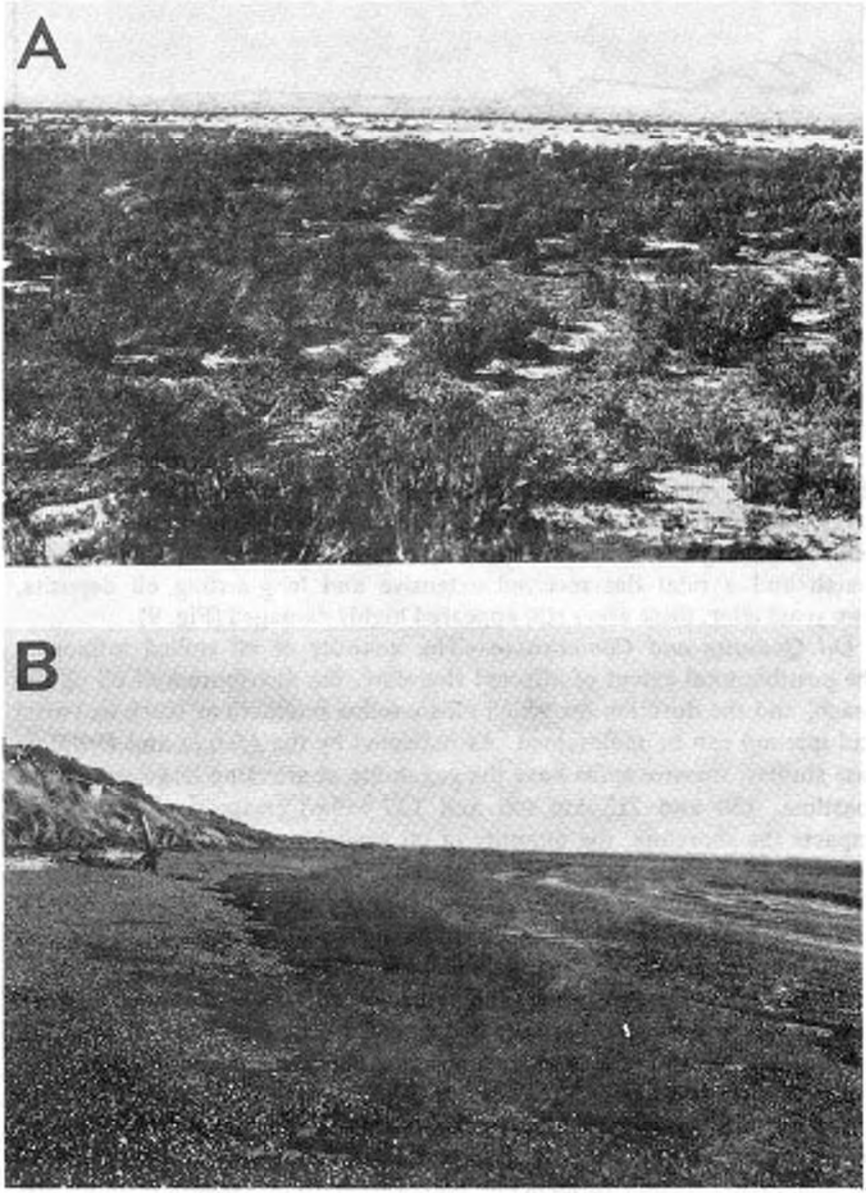

FIG. 9—*Two heavily damaged areas within* Metula *spill site, two years after the spill.* (A) *A devastated marsh in the East Estuary, south side of the First Narrows, Strait of Magellan.* (B) *Oil pavement bordering a sheltered tidal flat within the West Estuary, south side of the First Narrows, Strait of Magellan.*

influences the depth of penetration once a slick impacts a shoreline. Low-viscosity oils are able to penetrate deeper into the beach.

Interaction with Ice—Surface ice, where present to any large extent, plays an important role in the dispersal of spilled oil. In general, the aerial extent of oil dispersal in environments covered with ice is orders of magnitude smaller than during open-water spills [*24-26*]. When the ice melts or breaks up, however, it may transport much of the spilled oil, possibly contaminating previously unaffected areas. Spilled oil tends to accumulate in pools within open-water areas in sea ice. Oil may also become trapped in concavities under the ice. In general, oil is moved by tidal currents and accumulates in areas on the water's surface because of density differences. In addition, significant oil penetration may occur because of the high porosity of granular ice. As observed during studies of both the Buzzards Bay and Hudson River spills, shorefast ice often acts as a natural barrier to spilled oil, thereby preventing contamination of the shoreline. Oil moving under the ice toward the shore usually surfaces at the contact between bottom shorefast ice and floating shorefast ice. Movement of the oil landward of that point is unlikely. Use of oil spill control methods to protect shore environments shielded by shorefast ice is usually unnecessary.

Vulnerability Index

Using the previously discussed physical processes and shoreline characteristics, as well as initial biological effects and long-term oil persistence, we have developed a classification of coastal environments according to potential vulnerability to oil spill damage [27]. These environments are listed in the following on a scale of 1 to 10 and in order of increasing vulnerability. Photographs of each shoreline type are presented in Fig. 10.

1. *Exposed, Steeply Dipping or Cliffed Rocky Headlands*—Location: northern New England and along the Pacific Coast. Under high wave energy, oncoming waves forcefully reflect back, usually generating a return flow that prevents most oil from hitting the shoreline. Oil spill cleanup is usually unnecessary because of the low level of contamination.

2. *Eroding Wave-Cut Platforms*—Location: Long Island, southern New England, Cape Cod, and along the Pacific Coast. Wave action is also high along this coastal type, causing a rapid dissipation of spilled oil, generally within weeks. In most cases, cleanup is not necessary.

3. *Flat, Fine-Sand Beaches*—Location: especially prevalent along the southeastern Atlantic Coast. Oil penetration is restricted to only a few centimeters due to the close packing of the sediment. Burial of deposited oil is also minor. Oil usually forms as a thin surface layer which can be efficiently scraped off under proper supervision. Cleanup efforts should concentrate on removing oil from along the high-tide swash zone. In

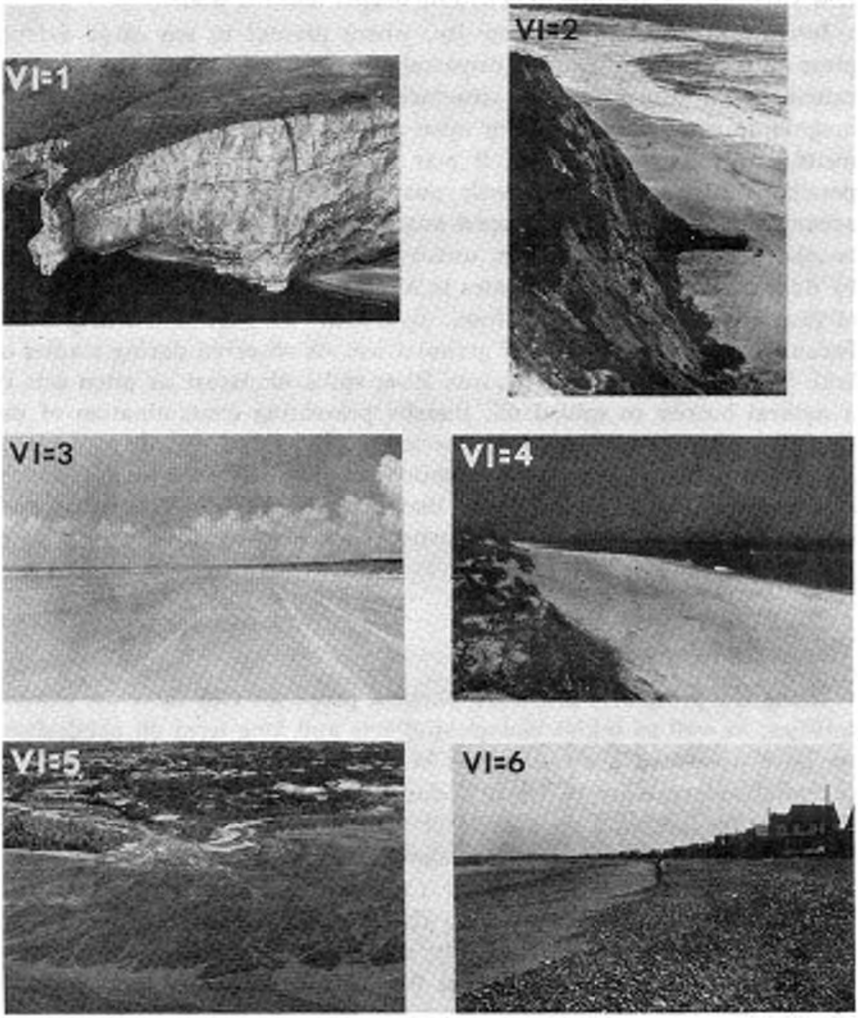

FIG. 10—*Shoreline environments of the Vulnerability Index (VI). Values are in order of increasing damage by oil: (VI = 1) Exposed, steeply dipping or cliffed rocky headlands; location—south of Baldwin Peninsula (Kotzebue Sound, Alaska). (VI = 2) Eroding wave-cut platforms; location—north of Santa Cruz, Calif. (VI = 3) Fine-sand beaches; location—Kiawah Island, S.C. (VI = 4) Coarse-sand beaches; location—Cape Cod, Mass. (VI = 5) Exposed, compacted tidal flats; location—Halibut Creek delta, Cook Inlet, Alaska. (VI = 6) Mixed sand and gravel beaches; location—Nantasket Beach, Mass. (VI = 7) Gravel beaches; location—North Scituate Beach, Mass. (VI = 8) Sheltered rocky coasts; location—McNeil Cove, Cook Inlet, Alaska. (VI = 9) Sheltered tidal flats, location—Cook Inlet, Alaska. (VI = 9) Sheltered tidal flats, location—Cook Inlet, Alaska. (VI = 10) Salt marshes; location—Kiawah Island, S.C.*

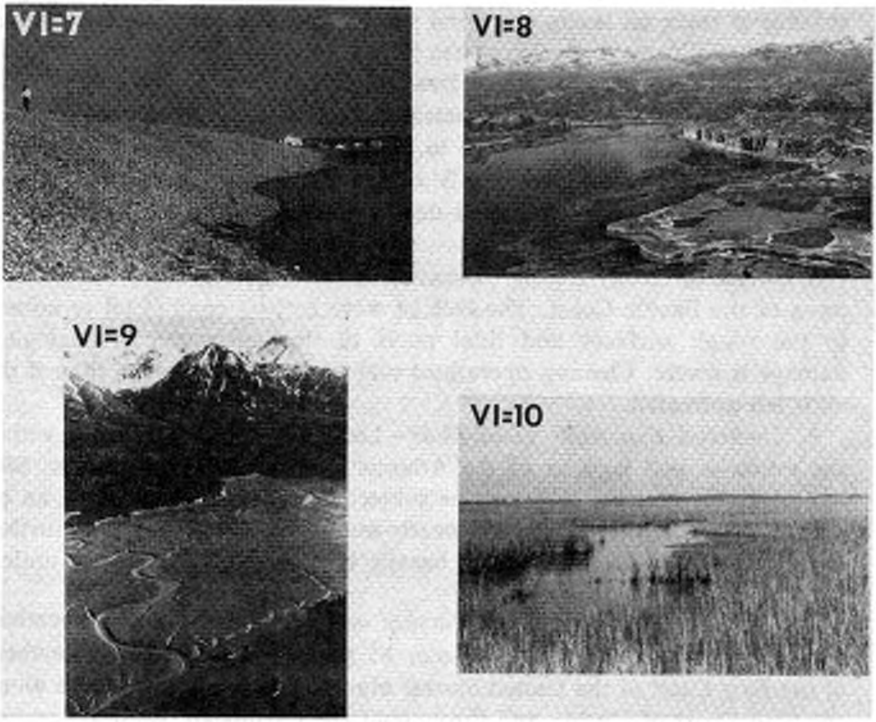

FIG. 10—*Continued.*

general, the lower portions of the beach are rapidly cleared of oil by natural wave action.

4. *Steeper, Medium- to Coarse-Grained Beaches*—Location: along most coasts of the United States. Oncoming oil generally forms thick oiled-sediment layers and mixes deep into the beach [50 to 100 cm (20 to 40 in.) in Spain]. Cleanup is difficult without damaging the beach. As before, cleanup should concentrate on removing oil from along the high-tide swash zone.

5. *Exposed, Compacted Tidal Flats*—Location: Bay of Fundy, Cape Cod Bay, and Alaska. Oil does not penetrate into the compacted surface of these flats. Minor wave activity generally succeeds in pushing the oil across the flat and onto the beach at its edge. Actual oil deposition is minor, although extensive biological damage may result. Cleanup of the flats should be considered only if oil contamination is very heavy.

6. *Mixed Sand and Gravel Beaches*—Location: New England, Nova

Scotia, and Alaska. Both penetration and burial occur rapidly. The persistence of thick oil layers on mixed sand and gravel beaches in the Strait of Magellan illustrates the long-term impact of oil in this environment.

7. *Gravel Beaches*—Location: New England, Nova Scotia and the Pacific Northwest. Oil is able to penetrate deeply into the coarse sediment of this beach type [up to 65 cm (26 in.) in Spain]. Under high wave energy conditions, oil can also be deeply buried under rapidly shifting gravel. Removal of all the oiled sediment during cleanup is likely to cause future erosion of the beach.

8. *Sheltered Rocky Coasts*—Location: New England, Nova Scotia, and parts of the Pacific Coast. The lack of wave activity enables oil to adhere to the rough surfaces and tidal pools of this environment. Biological damage is severe. Cleanup operations may cause more damage than if the oil is left untreated.

9. *Sheltered Estuarine Tidal Flats*—Location: commonly occur within the estuaries and lagoons of the Atlantic, Pacific and Gulf Coasts. Biological life is extensive and may be subject to long-term damage by an oil spill. Removal of the pollutant is nearly impossible without causing further damage. Only if the flat is very heavily oiled should cleanup be undertaken.

10. *Sheltered Estuarine Salt Marshes and Mangrove Coasts*—Location: salt marshes are especially common in the large estuarine embayment of the East Coast of the United States. Mangrove coasts are common along the Gulf Coast of Florida and throughout the Caribbean. Both are among the most biologically productive of all marine environments [*1*,*2*,*28*]. Heavy oil contamination may cause long-term deleterious effects. Two years after the *Metula* spill, a heavily oiled salt marsh on the south side of the Strait of Magellan showed almost no recovery. Oil may continue to exist in this area for ten or more years. Mangrove coasts impacted by oil also show serious long-term effects [*29*,*30*].

Coral Reefs—Location: common along Caribbean shoreline. The effect of oil on coral reefs is as yet unresolved. Corals vary in sensitivity to oil pollution and are negatively affected by some dispersants [*31*–*33*]. However, coral reefs in areas of small oil spillage have entirely escaped damage [*29*–*34*]. Tentatively, we have placed coral reefs at 7 to 8 on the Vulnerability Index.

This method of coastal classification is a useful means of delineating environments in spill-prone areas as part of a comprehensive oil-spill contingency plan. The usually limited supply of oil-spill control equipment can best be utilized by knowing where oil-sensitive areas are located. In this way, shoreline environments designated as particularly vulnerable to oil spill damage (Index values, 8 to 10) can receive priority protection. Areas in which oil has little long-term persistence (Index values 1 and 2) can be left alone. Coarse-grained beaches (Values 7 and 8) should be protected over beaches having finer grain size (Values 3 and 4). So far, the Vulnerability Index has been used to classify environments in lower Cook Inlet and the Copper River Delta, both in Alaska [*35-37*]. Research is presently underway to similarly classify the eastern half of the North Slope shoreline of Alaska [*38*].

Conclusions

Based on the study of four oil spills (*Metula, Urquiola, Bouchard #65*, and *Ethel H.*), and an extensive review of the literature, we are able to conclude the following:

1. The distribution and persistence of spilled oil is influenced by a complex interaction of the following factors: (1) wind stress and water currents, (2) beach activity and grain size, (3) tidal stage, (4) wave energy, (5) oil quantity and composition, and, where applicable, (6) ice effects.
2. The depth of oil burial and the thickness of oiled sediment increase as the grain size coarsens. Both are important in terms of beach cleanup.
3. Oil coming onshore during spring tidal conditions can have a particularly long-term impact on the beach because of oil deposition above major wave activity.
4. Natural processes should be allowed to clean the environment as much as possible.
5. Oil is rapidly removed from high-wave-energy areas; cleanup is usually unnecessary.
6. When applied, cleanup should concentrate on oil removal from the upper swash-zone portion of the beach.
7. More research is necessary to determine the influence of dispersants on oiled beaches.
8. Sheltered rocky coast, tidal flat, mangrove, and marsh environments should be cleaned only if oil accumulations are exceedingly heavy.
9. Under conditions of extensive shorefast ice, use of spill control methods to protect shore environments is usually unnecessary.
10. Shoreline environments react differently to spilled oil. In order of increasing vulnerability to oil spill damage, the environments of the Vulnerability Index are: (1) Exposed, steeply dipping, or cliffed rocky headlands; (2) eroding wave-cut platforms; (3) flat, fine-grained beaches; (4) steeper, medium- to coarse-grained beaches; (5) exposed, compacted tidal flats; (6) mixed sand and gravel beaches; (7) gravel beaches; (8) sheltered rocky coasts; (9) sheltered estuarine tidal flats; and (10) sheltered estuarine salt marshes and mangrove coasts. Coral reefs are tentatively placed at 7 to 8.

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References

[1] Teal, J. and Teal, M., *Life and Death of the Salt Marsh*, Ballantine Books, New York, 1969.

[2] Odum, W. E. and Skeij, S. S., *Coastal Zone Management Journal*, Vol. 1, 1975, pp. 141–163.

[3] "Pollution Incidents in and Around U.S. Waters, Calendar Year 1975," U.S. Coast Guard Report CG-487, Washington, D.C., 1977.

[4] Card, J. C., Ponce, P. V., and Snider, W. D. in *Proceedings*, Joint Conference on the Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., 1975, pp. 205–213.

[5] Hann, R. W., Jr., "Oil Pollution from the Tanker *Metula*," Report to the U.S. Coast Guard, Texas A&M University, Civil Engineering Department, College Station, Tex., 1974.

[6] Hann, R. W., Jr., "Follow-up Field Survey of the Oil Pollution from the Tanker *Metula*," Report of the U.S. Coast Guard, Texas A&M University, Civil Engineering Department, College Station, Tex., 1975.

[7] Gunnerson, C. G. and Peter, G., "The *Metula* Oil Spill," Marine Ecosystems Analysis Program (MESA), NOAA Environmental Research Laboratory, U.S. Government Printing Office, Washington, D.C., 1976.

[8] Hayes, M. O., and Gundlach, E. R., "Coastal Morphology and Sedimentation of the *Metula* Oil Spill Site in the Strait of Magellan," Report to the National Science Foundation—Research Applied to National Needs, Coastal Research Division, University of South Carolina, Columbia, S.C., 1975.

[9] Baker, J. M., Campodonico, I., Guzman, L., Texera, J. J., Texera, B., Venegas, C., and Sanhueza, A. in *Marine Ecology and Oil Pollution*, J. M. Baker, Ed., Halstead Press, New York, 1976, Chapter 18, pp. 441–471.

[10] Gundlach, E. R., Fischer, I. A., and Stein, R. J., *Oceans*, Vol. 10, 1977, pp. 56–60.

[11] Gundlach, E. R. and Hayes, M. O., *Marine Pollution Bulletin*, Vol. 8, pp. 132–136.

[12] Stein, R. J., Gundlach, E. R., and Hayes, M. O., "The *Urquiola* Oil Spill: Observations of Biological Damage Along the Spanish Coast," *Proceedings*, Conference on Assessment of the Ecological Impacts of Oil Spills, American Institute of Biological Sciences, Arlington, Va., 1978, in press.

[13] Ruby, C. H., Ward, L. G., Fischer, I. A., and Brown, P. J., "Buzzards Bay Oil Spill—An Arctic Analogue" in *Proceedings*, Conference on Port and Ocean Engineering under Arctic Conditions, Newfoundland, Sept. 1977, in press.

[14] Hayes, M. O., Owens, E. H., Hubbard, D. K., and Abele, R. W. in *Coastal Geomorphology*, D. R. Coates, Ed., *Proceedings*, 3rd Annual Geomorphology Symposium Series, Binghamton, N.Y., 1972, pp. 11–41.

[15] Blount, A. E., "Two Years After the *Metula* Oil Spill, Strait of Magellan, Chile: Oil

Interaction with Coastal Environments," Technical Report No. CRD-16, Department of Geology, University of South Carolina, Columbia, S.C., 1978.

[16] Gundlach, E. R., Ruby, C. H., and Blount, A. E., "*Urquiola* Oil Spill: Impact and Reaction on Beaches and Rocky Coasts," *Environmental Geology*, in press.

[17] Folk, R. L., *Petrology of Sedimentary Rocks*, Hemphill's, Drawer M, University Station, Austin, Tex., 1968.

[18] Nelson-Smith, A., *Oil Pollution and Marine Ecology*, ELEK Sciences, London, 1972, pp. 71–84.

[19] King, C. A. M., *Beaches and Coasts*, Edward Arnold Ltd., London, 1972, pp. 417–422.

[20] "Cleaning Oil Contaminated Beaches with Chemicals," Northeast Region Research and Development Program, Edison, N.Y., Federal Water Pollution Control Administration, Department of Interior, Washington, D.C., Program No. 15080 FHS 08/69, 1969.

[21] Duerden, F. C., "Spill in Portugal: A Report of the *Jakob Maersk* Incident," Environmental Protection Service, Environment Canada, Report No. EPS-8-EC-76-1, 1975.

[22] "Tide tables, 1974, West Coast of North and South America," Department of Commerce, NOAA-NOS, Washington, D.C., 1973.

[23] "Anuario de Mareas—1976," Instituto Hidrografico de la Marina, Cadiz, Spain, 1975, pp. 27–29.

[24] Mackay, D., Charles, M. E., and Phillips, D. R., "The Physical Aspects of Crude Oil Spills in Northern Terrain," Northern Pipeline Task Force on Northern Oil Development, Report No. 73-42, 1974.

[25] Isakson, J. S., Storie, J. M., Vaquers, Erickson, G. A., Kruger, J. F., and Corlett, R. J., "Comparison of Ecological Impacts of Postulated Oil Spills at Selected Alaskan Locations," U.S. Coast Guard, Final Report CG-D-155-75, 1975.

[26] Hoult, D. P., "Oil in The Arctic," Office of Research and Development, U.S. Coast Guard, Report CG-D-96-75, 1975.

[27] Gundlach, E. R. and Hayes, M. O., "Vulnerability of Coastal Environments to Oil Spill Impacts," *Marine Technology Society Journal*, in press.

[28] Odum, W. E. and Johannes, R. E. in *Tropical Marine Pollution*, E. J. F. Wood and R. E. Johnson, Eds., Elsevier Scientific Publications, N.Y., 1971, pp. 52–62.

[29] Chan, E. I. in *Proceedings*, Joint Conference on the Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., 1977, pp. 539–545.

[30] Nadeau, R. J. and Berquist, E. T. in *Proceedings*, Joint Conference of the Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., 1977, pp. 535–538.

[31] Lewis, L. G., *Marine Pollution Bulletin*, Vol. 2, 1971, pp. 59–62.

[32] Elgerschuizen, J. H. B. W., and de Kruijf, H. A. M., *Marine Pollution Bulletin*, Vol. 7, 1976, pp. 22–25.

[33] Reimer, A. A., *Marine Pollution Bulletin*, Vol. 6, 1975, pp. 22–25.

[34] Spooner, M., *Marine Pollution Bulletin*, Vol. 1, 1970, pp. 166–167.

[35] Hayes, M. O., Brown, P. J., and Michel, J., "Coastal Morphology and Sedimentation, Lower Cook Inlet, Alaska: With Emphasis on Potential Oil Spill Impacts," Technical Report No. 12-CRD, Department of Geology, University of South Carolina, Columbia, S.C., 1976.

[36] Hayes, M. O., Michel, J., and Brown, P. J., "Vulnerability of Coastal Environments of Lower Cook Inlet, Alaska to Oil Spill Impact" in *Proceedings*, Conference on Port and Ocean Engineering under Arctic Conditions, Newfoundland, Sept. 1977, in press.

[37] Ruby, C. H., "Coastal Morphology, Oil Spill Vulnerability and Sedimentation of the Northern Gulf of Alaska," Technical Report No. CRD-15, Department of Geology, University of South Carolina, Columbia, S.C., 1977.

[38] Nummedal, D. (principal investigator), "Vulnerability Index for the Beaufort Sea Coast of Alaska," Department of Geology, University of South Carolina, Columbia, S.C., research in progress.