3 Sensitivity of Coastal Environments to Oil

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Chapter 3.
Sensitivity of Coastal Environments to Oil

Introduction

Intertidal habitats are at risk during spills because of the high likelihood of being directly oiled when floating slicks impact the shoreline. Oil fate and effects vary significantly by shoreline type, and many cleanup methods are shoreline-specific. The concept of mapping coastal environments and ranking them on a scale of relative sensitivity was originally developed in 1976 for lower Cook Inlet (Michel et al., 1978). Since that time, the ranking system has been refined and expanded to cover shoreline types for all of North America, including the Great Lakes and riverine environments.

Prediction of the behavior of oil on intertidal habitats is based on an understanding of the coastal environment, not just the substrate type and grain size. The sensitivity of a particular intertidal habitat is an integration of the:

1) Shoreline type (substrate, grain size, tidal elevation, origin),
2) Exposure to wave and tidal energy,
3) Analysis of the natural persistence of the oil on the shoreline,
4) Biological productivity and sensitivity, and
5) Ease of cleanup without causing more harm.

All of these factors are used to determine the relative sensitivity of shorelines. Key to the sensitivity ranking is an understanding of the relationships between physical processes and substrate which produce specific geomorphic shoreline types and predictable patterns in oil behavior and sediment transport patterns. In the following sections, the definition, morphology and processes, and oil behavior for six general coastal environments are summarized.

Exposed Rocky Coasts

Although exposed rocky coasts can be highly variable in elevation, slope, exposure, crenulation, and biological utilization, they can be divided into two broad types, based on the behavior and persistence of oil: wave-cut cliffs and wave-cut rock platforms. Both types are characterized by strong waves which wash across the intertidal zone and, except where very large waves occur, a rich biological community. In general, oil persistence is low because the oil does not penetrate the substrate and so it is available for rapid removal by wave action. But, both types can have complex micro-environments in the form of sheltered crevices and wave-shadow pockets behind large boulders or offshore rocks. They differ in the slope and width of the intertidal zone, the presence of sediments, and wave reflection patterns. Each type is discussed below.

Wave-cut Cliffs

This shoreline type has a steep intertidal zone with very little width. The rock surface can be highly irregular, with numerous cracks and crevices. Sediment accumulations (gravel- to boulder-sized material) are uncommon and usually ephemeral, since waves remove the debris of mass wasting as the sea cliffs retreat. Wave-cut cliffs are found interspersed with other shoreline types, particularly wave-cut platforms.

The narrowness of the intertidal zone limits to some degree the extent of biological colonization, which must also be able to survive the intense wave action. There is strong vertical zonation of biological communities, with animals dominating the mid- to upper intertidal zone, and algae dominating the lower intertidal zone. Offshore, large kelp beds can occur, providing habitat for a wide range of organisms. The ruggedness and isolation of rocky headlands make them important as nesting sites for seabirds.

Observations at many oil spills have shown that:

- Oil is held offshore by waves reflecting off the steep cliffs
- Any oil that is deposited is rapidly removed from exposed faces
- The most resistant oil would remain as a patchy band at or above the high-tide line
- Impacts to intertidal communities are expected to be of short duration

- An exception would be where heavy concentrations of a light refined product (e.g., No.2 fuel oil) came ashore very quickly

- Greatest impacts are likely to be to birds when present at nesting colonies or feeding in nearshore waters

Because of the low potential for oil accumulation and high degree of natural cleansing, wave-cut cliffs have been ranked as having the lowest sensitivity of all natural intertidal habitats.

Wave-Cut Platforms

Where erosion has formed a flat rock bench within the intertidal zone, it is referred to as a wave-cut platform (or shore platform). The width of platforms can range from a few meters to nearly a kilometer. Somewhat surprisingly, there is no consensus as to how they are formed; studies have proposed, in addition to wave action, ice scouring during either or both glacial and modern periods, salt weathering, mechanical fracture by freeze and thaw action, and biological weakening of the rock. However, it has been shown that many platforms are very young, maybe taking only up to a thousand or a few thousand years to form. (How else could the present platforms keep up with sea-level rise?)

Wave-cut platforms can be characterized as follows:

- They are composed of a rock bench, of highly variable width

- The shoreline may be backed by a steep scarp or low bluff

- There may be a narrow, perched beach of gravel- to boulder-sized sediments at the base of the scarp

- The platform surface is irregular and tidal pools are common

- Small accumulations of gravel can be found in the tidal pools and crevices

- Pockets of sandy "tidal flats" can occur on the platform in less exposed settings

- These habitats can support large populations of encrusting animals and plants, with rich tidal pool communities

- They can be used as haulouts by marine mammals

Even though they are exposed to high wave energy, there are two factors which make wave-cut platforms more sensitive to oil spill impacts than wave-cut cliffs.

First, oil may penetrate and persist longer in the beach sediments, if present. This oil would be removed only when large waves reworked the sediments. There can be a wide variability in the rate of reworking along a shoreline segment, depending upon the width of the platform, fetch, shoreline orientation, and the presence of offshore rocks which refract waves. The latter condition can result in accumulation and persistence of oil due to what we term the *tombolo effect*, which is illustrated in Figure 3-1. A *tombolo* is a spit-like projection of unconsolidated sediment that forms behind an offshore island or bedrock outcrop. The tombolo is the accumulation of sediment which forms as a result of wave refraction bending around the island or bedrock outcrop, where the refracted waves meet in the lee of the offshore obstruction. The important point is that wave energy is lower in the lee of the tombolo, and any stranded oil tends to persist much longer there. For example, Figure 3-1 shows that oil from the *Exxon Valdez* oil spill in Alaska remained over one year in a very high energy setting as a result of the protection (from wave attack) afforded by the offshore rock outcrops on the wave-cut platform.

The second factor which increases the sensitivity of wave-cut platforms is the potential for greater impacts to intertidal communities. Although oil does not adhere to the wet rock surfaces, heavy accumulations of oil can temporarily cover the intertidal zone during falling tides. Tidal pool organisms can be killed by smothering or exposure to the toxic fractions of fresh oil or refined products. Also, marine mammals using the platforms as haulouts can be directly oiled.

Oil behavior on wave-cut platforms can be summarized as follows:

- Oil will not adhere to the rock platform, but rather be transported across the platform and accumulate along the high-tide line
- Oil can penetrate and persist in the beach sediments, if present
- Persistence of oiled sediments is usually short-term, except in wave shadows or larger sediment accumulations

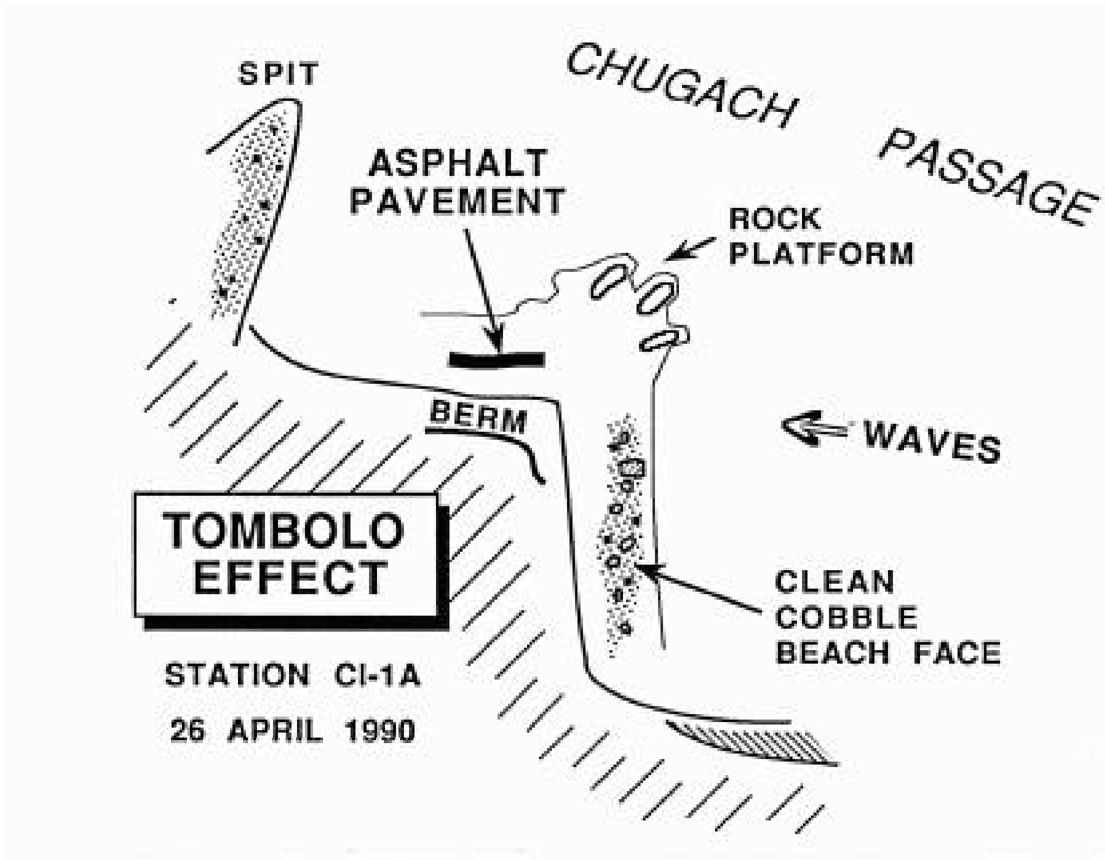


Figure 3-1. Example of the tombolo effect at the *Exxon Valdez* spill site. (From Hayes et al., 1990; Fig. 4.)

Sand Beaches

Introduction

A beach is an accumulation of unconsolidated sediment that is transported and molded into characteristic forms by wave-generated water motion. Beaches will form virtually anywhere sediment is available and there is a site for sediment accumulation. Inherent to sand beaches is change, over timescales ranging from seconds to years. Knowing the patterns of change enables us to better predict the behavior of oil spills and the persistence of oiled sediments. Sand beaches vary widely in their grain size, width, slope, origin, exposure to waves, and sediment transport patterns, and geologists and engineers have devised many types and models to describe them. In contrast, biologists seldom differentiate among sand beaches and consider them to have simple biological communities.

Figure 3-2 shows a typical beach profile and common terminology. Starting at the water level (WL), a low-tide terrace forms a flat, hard-packed, and water-saturated surface. Over this surface, sand which was eroded from the beach by storm waves migrates in the form of intertidal bars (ridges) up to 1 meter in height. The depression in front of the ridge is called a runnel. Eventually, the ridge welds onto the beach, forming a berm at the high-tide line. Note that the berm top slopes gently landward, forming a berm runnel. During the depositional stages on a beach, multiple berms can form. It should also be noted that deposition of the berm can build up to 2 meters of sand over a period of weeks to months. The beachface extends from the berm crest to the low-tide terrace and is steeply inclined toward the sea.

From the perspective of oil behavior on beaches, there are three basic factors:

1) The depth of oil penetration into the sediments

2) The potential for burial of oiled layers by clean sediments

3) The ability of the sediment to support equipment

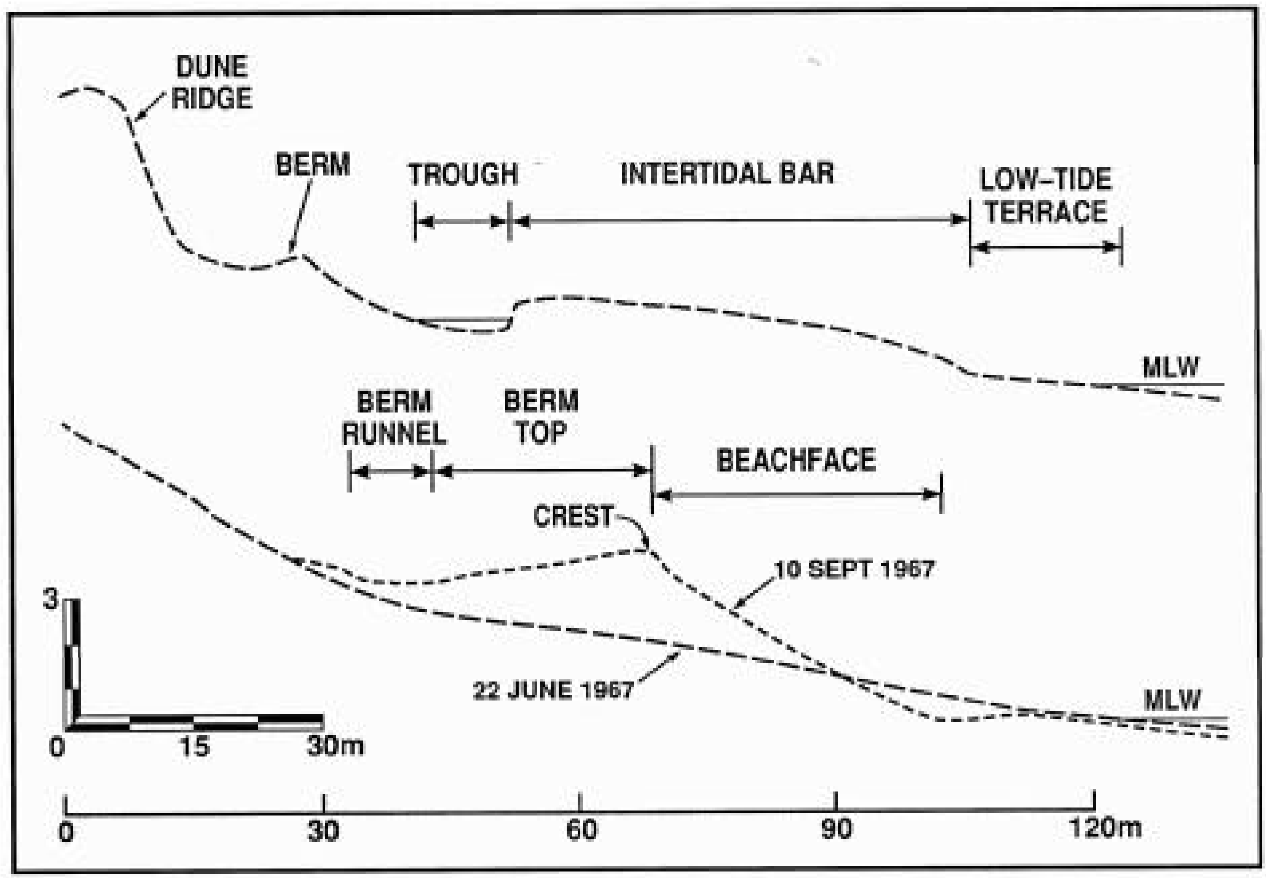


Figure 3-2. Three of the more common types of beach profiles occurring on sand beaches. Examples from Plum Island, Massachusetts. The upper profile, a constructional profile, occurs when beach is recovering from an erosional episode. The intertidal bar migrates landward, accretes to the beach, and a major accretional berm (mature profile; one labeled 10 Sept. 1967) results. The flat, post-storm profile (labeled 22 June 1967) occurred after a brief summer storm. (After Hayes and Boothroyd, 1969; Figs. 4 and 5.)

Morphology and Sediment Transport

The grain size of a beach shows a distinct relationship to the slope of the beachface–the coarser the sand, the steeper the beachface. The beach slope is also controlled by wave activity in that eroding beaches tend to flatten and accreting beach steepen. Figure 3-3 illustrates the relationship of beach slope to grain size and degree of exposure. Knowledge of the sediment transport patterns for sand beaches is important for understanding how oil behaves on them.

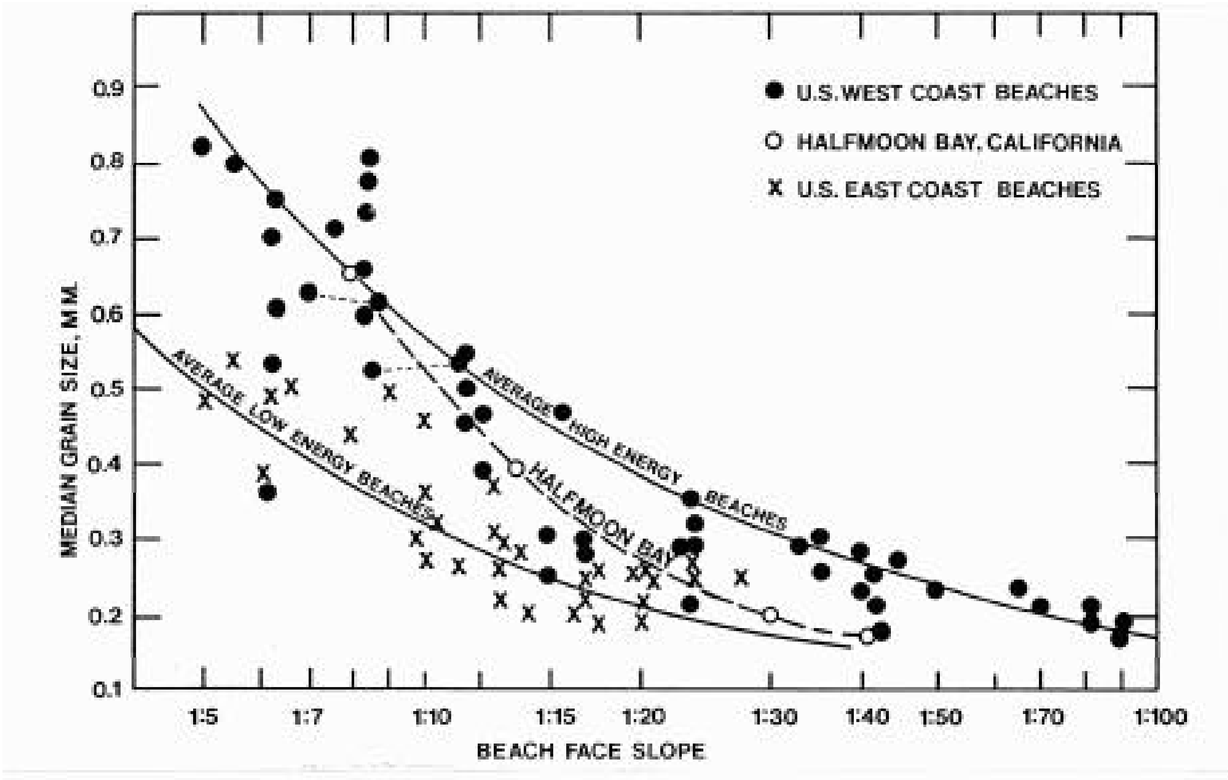


Figure 3-3. Relationship of beach grain size to beachface slope on the east and west coasts of North America. The more exposed beaches of the west coast tend to have flatter slopes because of the large volumes of backwash produced by the larger waves. Halfmoon Bay, California, is partially sheltered by a headland, so its data points fall between the two extremes. (From Komar, 1976, Fig. 11-8; based on data of Bascom, 1951 and Wiegel, 1946.)

Sand is moved alongshore on beaches by two mechanisms. Under oblique wave approach, the paths of moving sand grains on the beachface follow a saw-tooth pattern as the wave uprush pushes the grains obliquely up the beach and they roll straight down the slope as gravity pulls back the backwash. Also, the continuous action of the oblique waves induces a longshore current which carries sediment parallel to shore. Both processes are simply illustrated in Figure 3-4, although complex sediment circulation patterns can form complicated bar and rip systems.

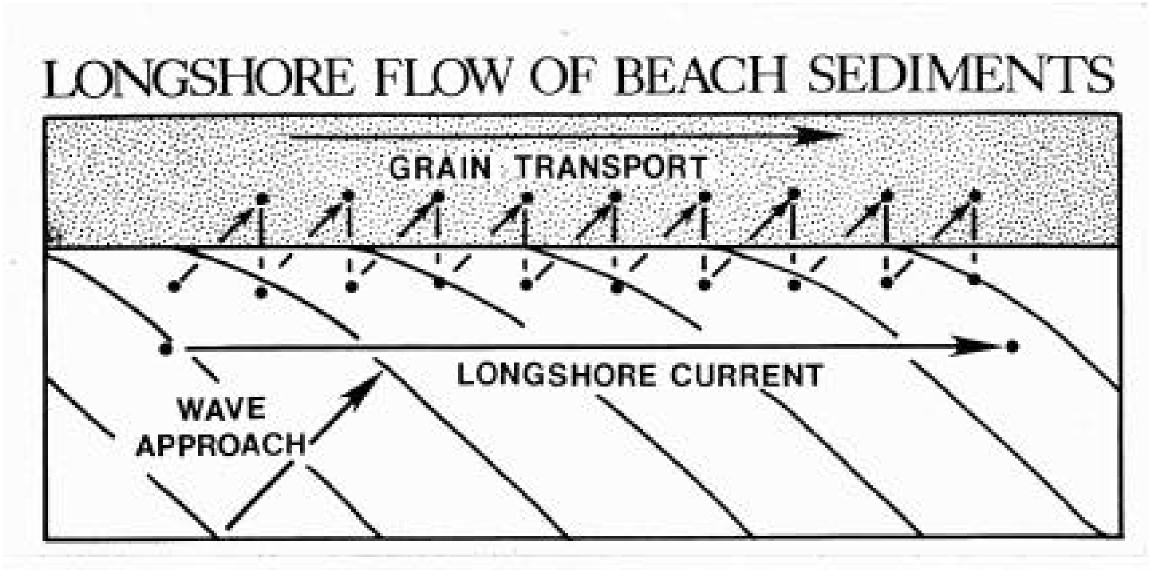


Figure 3-4. Longshore motion of beach sediment produced by wave swash and wave-generated current action when waves approach the shoreline at an angle. (From Bird, 1968.)

The erosion and deposition of sand on beaches is known as the ***beach cycle***. The concept of the cyclical change of beaches from a flat, erosional profile in winter to a wide, depositional berm in summer is well ingrained in both the popular and scientific literature. The concept originated from detailed studies on the west coast of the United States (Shepard, 1950; Bascom, 1954). Generally speaking, storm waves which erode sand from the beach are more common in the winter, whereas flatter, depositional swell waves are more common in the summer on the California coast–hence the terms *summer* and *winter* profiles. Figure 3-5 shows the deposition at Carmel, California during the summer and the subsequent erosion triggered by big winter storms. However, this strong seasonal storm pattern is not present along other coasts, and the more appropriate terminology is to refer to the beach profile as the post-storm, constructional, or mature (fully accretional) profile.

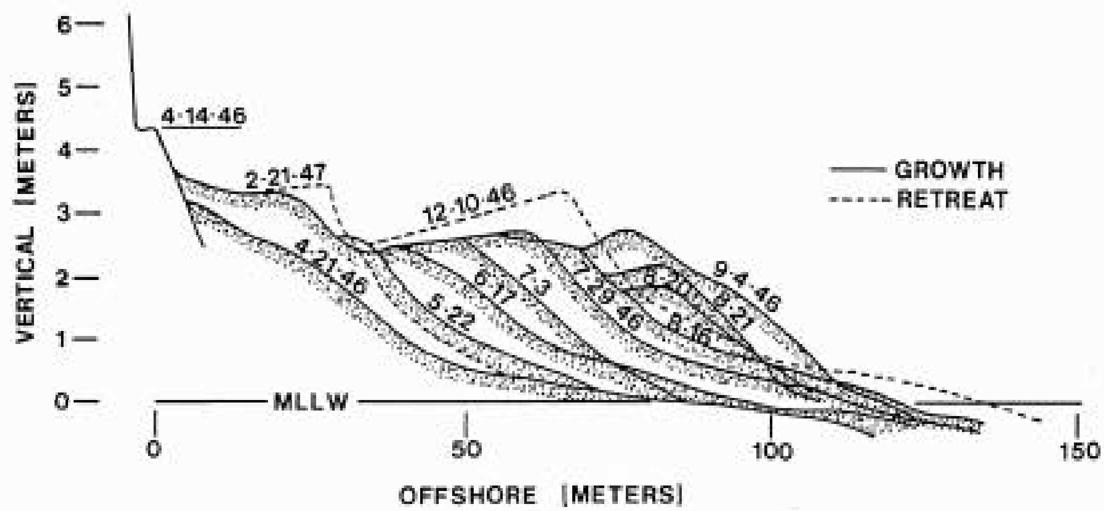


Figure 3-5. Growth and retreat of beach berm at Carmel, California between 14 April 1946 and 21 February 1947 (after Bascom, 1954). These and other observations on the California coast gave birth to the concept of winter and summer beach profiles.

The stage of the beach cycle determines the rate and amount of sediment accumulation on beaches, and hence the potential for burial of oiled layers by clean sand or removal of oiled sediment by erosion. For oil spill analysis, sand beaches can be divided into two basic types, fine-grained and coarse-grained, which are compared and contrasted in the following sections.

Fine-grained Sand Beaches

The grain size of sediment on fine-grained sand beaches ranges between 0.0625 and 0.25 millimeters (mm). The compact sediments prevent deep penetration of oil. On exposed shorelines, the beaches are generally flat, wide, and hard-packed. Along more sheltered bays and lagoons, the beaches are still flat but much narrower and commonly fronted by tidal flats. Because of this flat profile, they change very slowly in response to changing wave and tidal conditions. The importance of this characteristic is best exemplified by observations at the *Urquiola* oil spill in Spain in 1976, shown by sequential beach profiles of a heavily oiled fine-grained sand beach in Figure 3-6 and described by Gundlach et al. (1978).

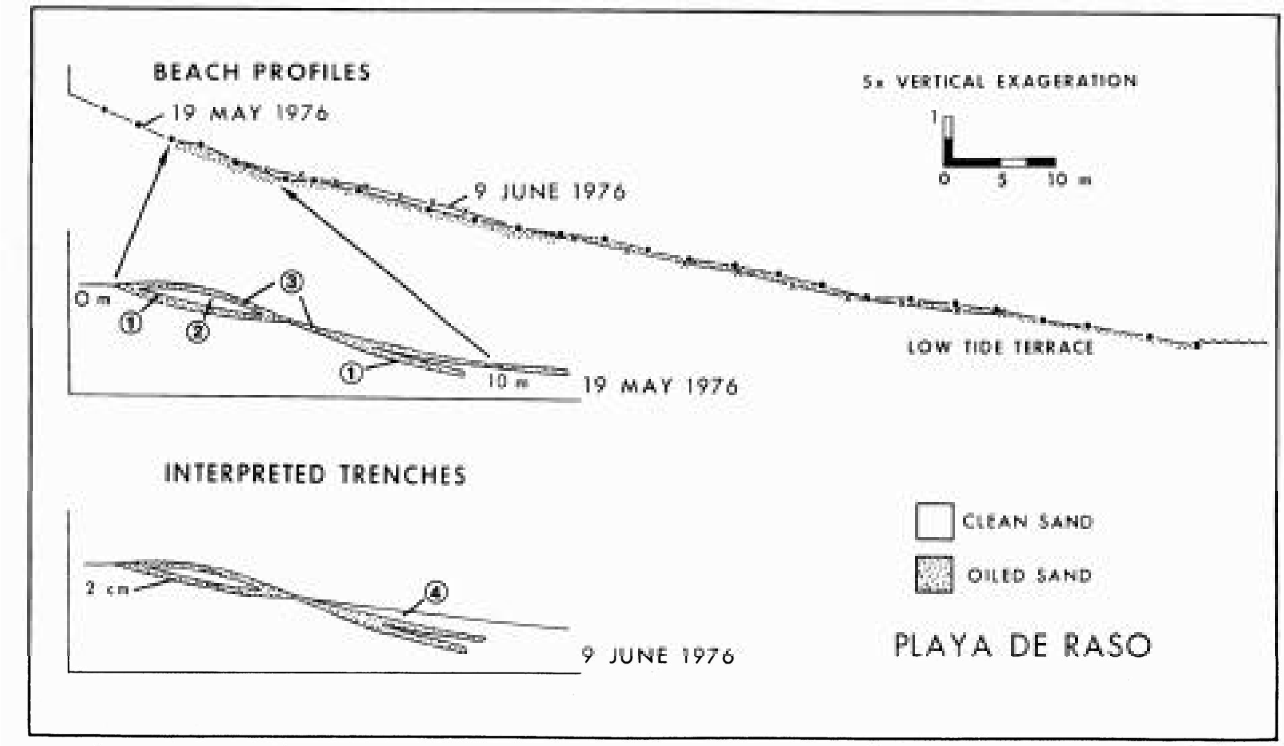


Figure 3-6. Beach profiles at the *Urquiola* oil-spill site, Plaza de Raso, Spain, plotted at 5:1 vertical exaggeration. Note the relatively shallow depths of oil penetration and burial on this fine-grained sand beach. Trenches are not drawn to scale. Circled numbers refer to the chronological sequence of depositional events (see text). (After Gundlach et al., 1978; Fig. 7.)

"Initially, 1-3 cm of oil covered the entire intertidal zone. The oil coating was strictly superficial owing to the close packing of the sediment. Comparison of the profiles taken on May 19 and June 9 (Fig. 3-6) illustrates minor, though important, variations in the morphology of the beach. During this time, the lower beachface lost 2 cm of sediment and oil, while the upper portions gained an equal amount of clean sediment. As a result of these subtle changes, oil was removed from 60 m of shore and buried along 23 m.

"Trenches dug in the oiled zone yield substantial information concerning the depositional history of the beach during and after initial oil impact. Interpreted trenches, illustrated in Figure 3-6, indicate the following depositional sequence: (1) burial of the oil deposited on the beachface before measurement of the first profile on May 19, (2) deposition of 3 cm of clean sand on the berm, (3) deposition of the thin surficial oil layer visible on the May 19 profile, and (4) deposition of clean sand over the oiled layers along the upper portion of the beach. Oil that was placed on the berm during the high spring tides of mid-May remained undisturbed throughout the study period."

The most important of these observations are that oil penetration was limited to a few centimeters and maximum burial of oil anywhere on the beach was about 10 cm. Measurements of oil penetration and burial were made at 19 heavily oiled beaches at the *Urquiola* oil spill, and the results are plotted in Figure 3-7. There is a good correlation between oil penetration and burial with grain size. Maximum penetration in fine-grained sand beaches was less than 10 cm and maximum burial over a three-week period was less than 20 cm.

Similar results have been observed at many other spills. Since most of the oil remains on or near the surface on fine-grained sand beaches, natural removal processes can be very effective, depending upon the frequency of storms. Usually, the first moderate storm will remove a significant amount of the oil. For example, oil from the *Ixtoc 1* well blowout accumulated on Texas beaches for nearly 30 days, until a tropical depression passed through, generating 1-2 m waves. After the storm, surveys showed that over 90 percent of the oil on the shoreline had been removed (Fig. 3-8), with no buried oil found on any of the fine-grained sand beaches. Only the mixed sand and shell beaches retained a significant amount of oil (Gundlach et al., 1981). Figure 3-9 shows the comparison of the changes in beach profile and oil distribution on fine-grained versus coarse-grained sand and shell hash beaches at the *Ixtoc 1* site. The storm completely reworked the fine-grained sand and removed all of the oil except for a light accumulation of tarballs at the landward limit of wave swash. On the coarse-grained beach, the storm eroded the beachface but deposited a 0.5m thick layer of sediments mixed with tarballs high on the backbeach.

At the *Amoco Cadiz* oil spill in France (March, 1978), most of the fine-grained sand beaches went from being heavily oiled to having a light oil coverage, usually with only a minor oiled swash line, within about a month (Gundlach and Hayes, 1978). By mid-summer, four months later, the fine-grained sand beaches were generally free of oil. However, in some localities, some discontinuous, oiled-sediment layers

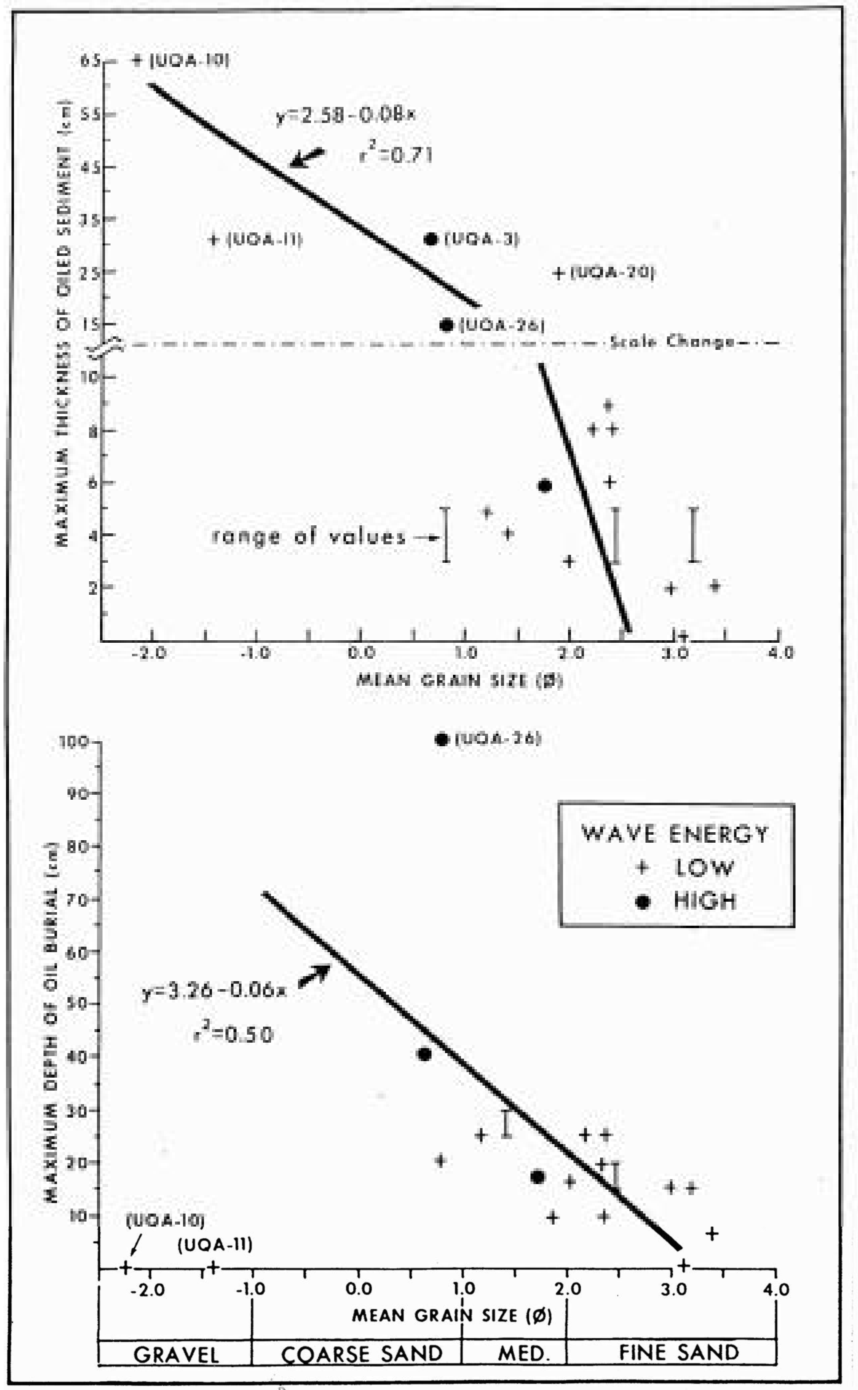


Figure 3-7. Relationship of thickness of oiled sediment layers and oil burial to sediment grain size at 19 oiled beaches at the *Urquiola* oil-spill site. The oil-layer thickness, a function of oil penetration, capillary forces and mixing of sediment and oil by wave action, clearly increases with an increase in grain size (upper curve; correlation coefficient [r^2] = 0.71). Depth of oil burial also increases with increasing grain size (lower curve). (From Gundlach et al., 1978; Fig. 6.)

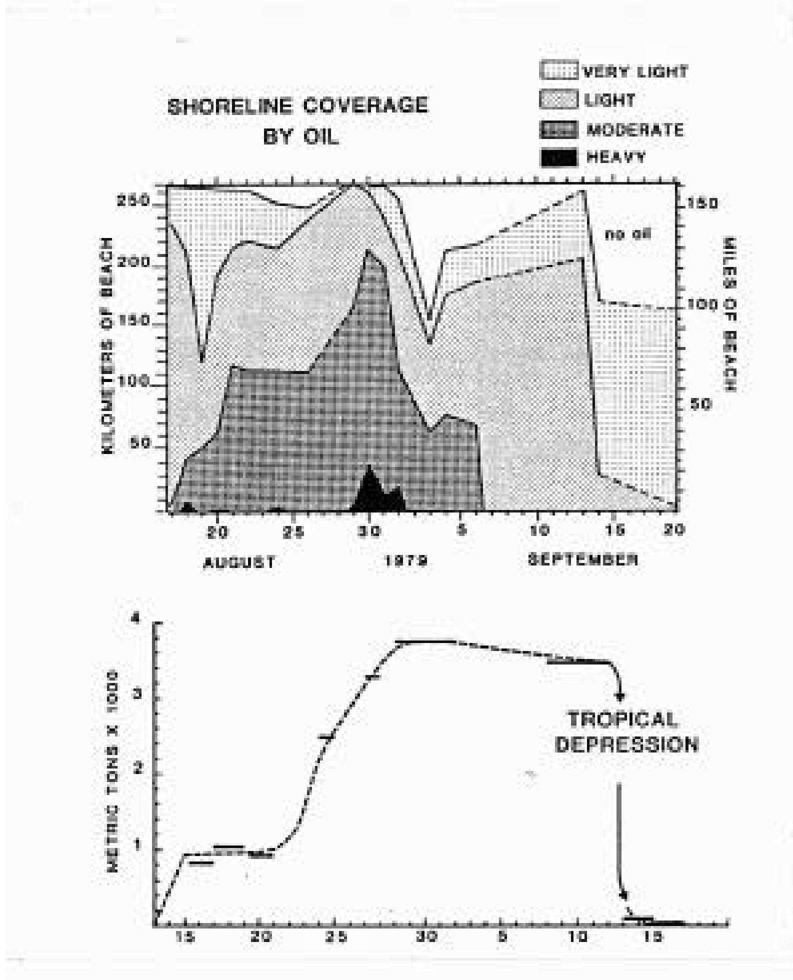


Figure 3-8. Oil coverage along the beach of Padre Island, Texas in August and September 1979 as result of *Ixtoc 1* spill. Note rapid cleaning of the beaches by wave action (1-2 m waves) resulting from passage of a tropical storm on 13 September. (From Gundlach et al., 1981; Fig. 3.)

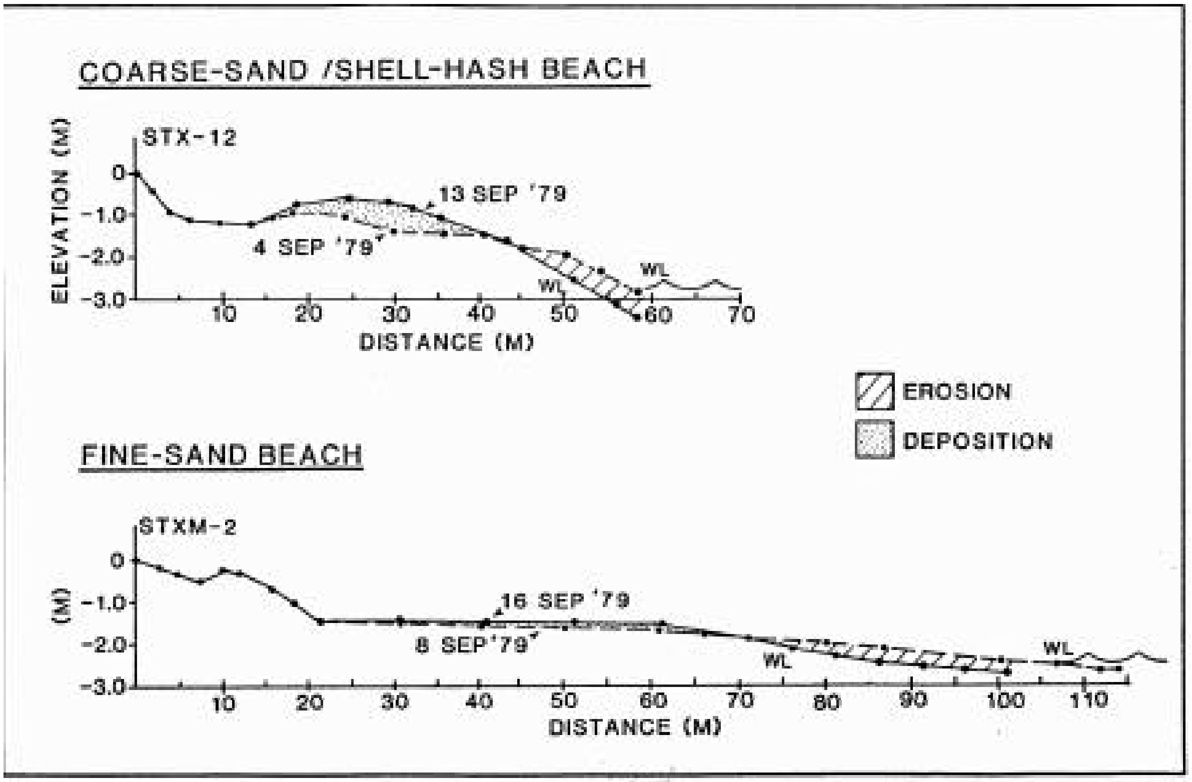


Figure 3-9. Beach profiles of two south Texas beaches that were oiled during the *Ixtoc 1* spill. The changes shown, brought about by the passage of a tropical storm, resulted in oil burial up to 70 cm on the coarse-sand/shell-hash beach and removal of most of the oil from the fine-grained sand beach. (From Gundlach et al., 1981; Fig. 6.)

persisted along the upper beachface until November 1978. All of the fine-grained sand beaches were located along the outer coast, in relatively exposed settings.

In more sheltered settings, oil will persist longer, but burial is less likely because of the low wave energy. Therefore, asphalt pavements may form in such areas if they are heavily oiled. In Saudi Arabia and Bahrain, there are asphalt pavements on sheltered sand beaches from spills up to ten years old. Because these types of beaches are narrow, the pavement can cover nearly the entire beachface. Once a pavement forms, it stabilizes the beach sediments to the degree that only very large, infrequent waves can slowly erode them.

Biological utilization of fine-grained sand beaches is usually low because of the lack of a stable, solid surface and the abrasive action of the moving sand. Epibiota are absent to rare, and infauna are found seasonally in low to moderate densities with a low diversity. Of the small, burrowing species, bivalves, polychaete worms, and crustaceans make up significant portions of the infaunal community on exposed beaches. At certain times of the year, large numbers of shorebirds may be present, feeding on these infauna.

The behavior and short-term impacts of oil on fine-grained sand beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will concentrate in a band along the high-tide line
- Under heavy accumulations, oil can cover the entire intertidal areas, although the oil will be lifted off the lower part of the beach with the rising tide
- Maximum penetration of oil into fine-grained sand will be less than 10 cm
- Burial of oiled layers by clean sand within the first few weeks after the spill will be limited usually to less than 30 cm along the upper beachface
- Deeper burial is possible if the oil is deposited at the beginning of an accretionary period
- Much of the oil will be removed during the next storm
- Biological impacts include temporary declines in infaunal populations, which can also affect feeding shorebirds
- The usually hard, compact sediments will support pedestrian and vehicular traffic

On sheltered beaches:

- More of the beachface can be covered because it is narrow
- Even less oil penetration occurs because the sediments are finer and can contain small amounts of silt and clay
- There is little to no likelihood of burial, except by wind-blown sand
- Depending on the degree of exposure to any waves, oil persistence can increase to months or years

- A moderately rich biological community can be supported
- Asphalt pavements can form under heavy accumulations; pavements will change nature and stability of the substrate and thus its biological utilization

Coarse-grained Sand Beaches

The grain size of sediment on coarse-grained sand beaches ranges between 0.25 and 2 mm. The more porous sediments allow penetration of oil up to 25 cm (Fig. 3-7). On exposed shorelines, the beaches are steeper and softer than fine-grained sand beaches, and the width is highly variable. Along more sheltered bays and lagoons, the beaches are steep but much narrower and commonly fronted by tidal flats. Coarse-grained sand beaches change rapidly in response to changing tidal and wave conditions, again as observed first at the *Urquiola* oil spill.

The processes are shown in Figure 3-10 and discussed by Gundlach et al. (1978), as follows:

> "As oil first came ashore on May 17 or 18, the runnel behind the spring berm acted as a trap for incoming oil. Pools of oil several centimeters thick remained in the berm runnel for several weeks. As inferred from the trenches illustrated in Figure 3-10, the following sequence of events probably occurred during and after initial oil impact. Alternative clean and oiled layers along the upper portion of the beach indicate that: (1) Oil slicks came ashore and were stranded during an accreting stage of spring berm development. Oil continued to come onshore as the tidal stage regressed toward neap. The neap berm formed as a result of constructional wave activity during this tidal stage. (2) Oil deposited at the time rapidly became incorporated into the accreting neap berm. (3) Oil pools formed in the neap berm runnel as more oil slicks came ashore. As the tidal cycle once again advanced toward spring conditions, after neap tides on May 20-23, the neap berm was partially destroyed and its sand distributed higher on the beach. (4) Oil previously deposited in the runnel of the neap berm was buried during this process. Remnants of this deposit are visible as discontinuous layers intersecting the beachface at high angles. During all stages, oiled sediment

was continuously reworked so the main portions of the beach still appeared heavily oiled on June 9, almost four weeks after the grounding."

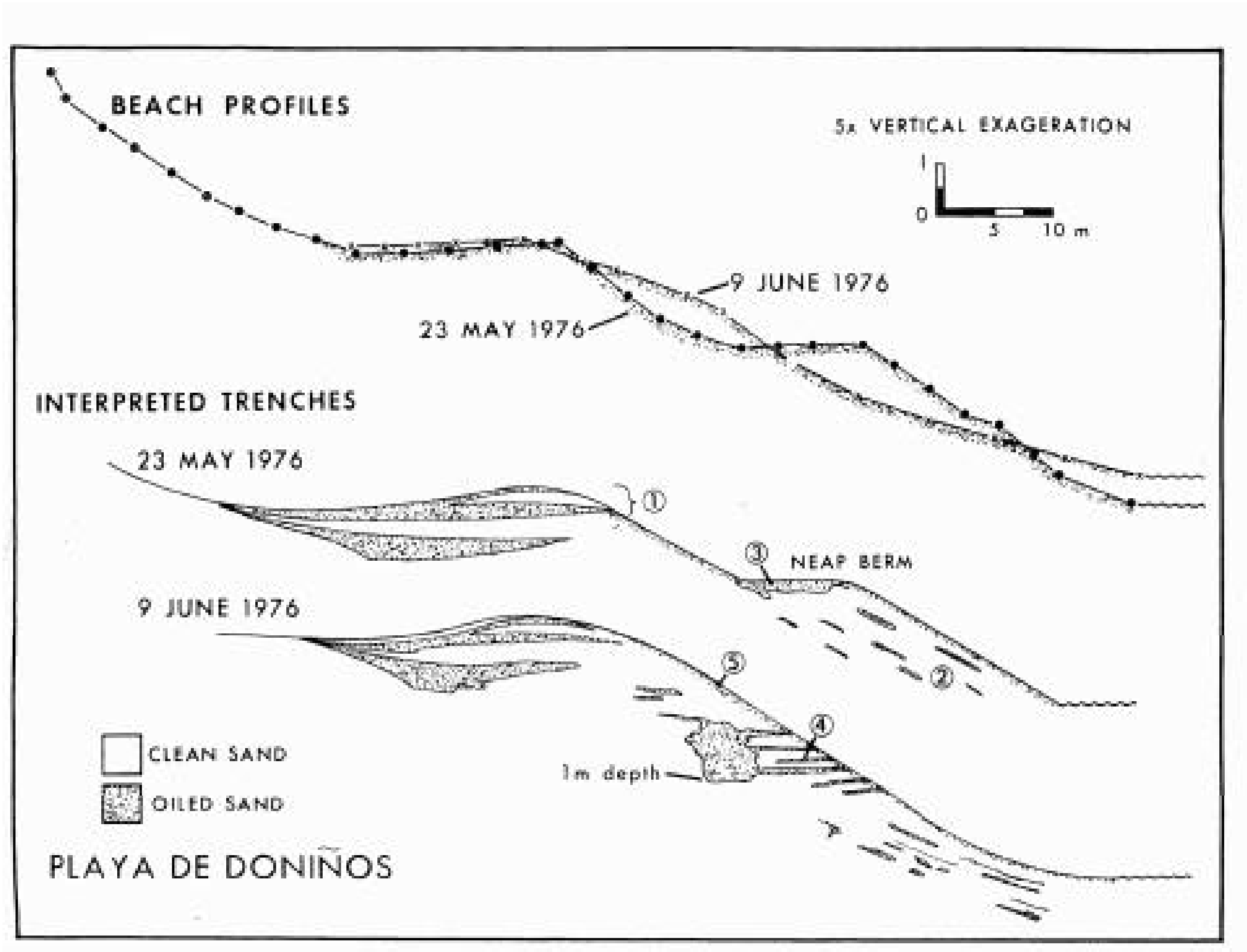


Figure 3-10. Burial of oil as result of beach-profile changes on a moderately oiled medium- to coarse-grained sand beach at the *Urquiola* spill site (Playa de Doñinos, Spain). Numbers refer to chronological sequence of depositional events (discussed in text). Trenches are not drawn to scale. (From Gundlach et al., 1978; Fig. 9.)

Coarse-grained sand beaches pose much greater oil persistence and cleanup problems than fine-grained sand beaches because of the deeper penetration and rapid burial. The stage of the beach cycle at the time of oil deposition will greatly affect the total potential depth of burial. If the oil strands just after a major storm, when the beach is at its erosional maximum, rapid depostion of clean sand can bury the oil until the next storm or perhaps the next storm season (e.g., in California). Figure 3-11 shows sequential profiles from a coarse-grained sand beach at the *Amoco Cadiz* oil spill. Continued deposition of clean sand from March to November resulted in burial up to 82 cm. During the *Ixtoc 1* spill in Texas, coarse-grained sand and shell beaches had a much greater amounts of buried oil than the fine-grained beaches (90 percent versus 37 percent, Fig. 3-12). In California, where there is strong storm seasonality, oil deposited on beaches in March or April could be buried by several meters of clean sediment and re-exposed 6-9 months later, causing re-oiling problems for the shoreline and wildlife.

There is a second mechanism by which oiled layers can be buried by clean sand, namely, migrating rhythmic topography. Figure 3-13 shows the process by which stranded oil could be buried by this alongshore erosional and depositional pattern. This shoreline pattern is most common on beaches with a sustained oblique wave approach.

Because of the mobility of coarse-grained sand beaches, they do not generally support a rich biological community. Some animals may be found in association with beach wrack, mostly amphipods and insects. Burrowing animals can be seasonally low to moderate in densities, but with low diversity and consisting of bivalves, crustaceans, and polychaetes. These beaches can be important resting and feeding habitat for shorebirds and coastal diving birds.

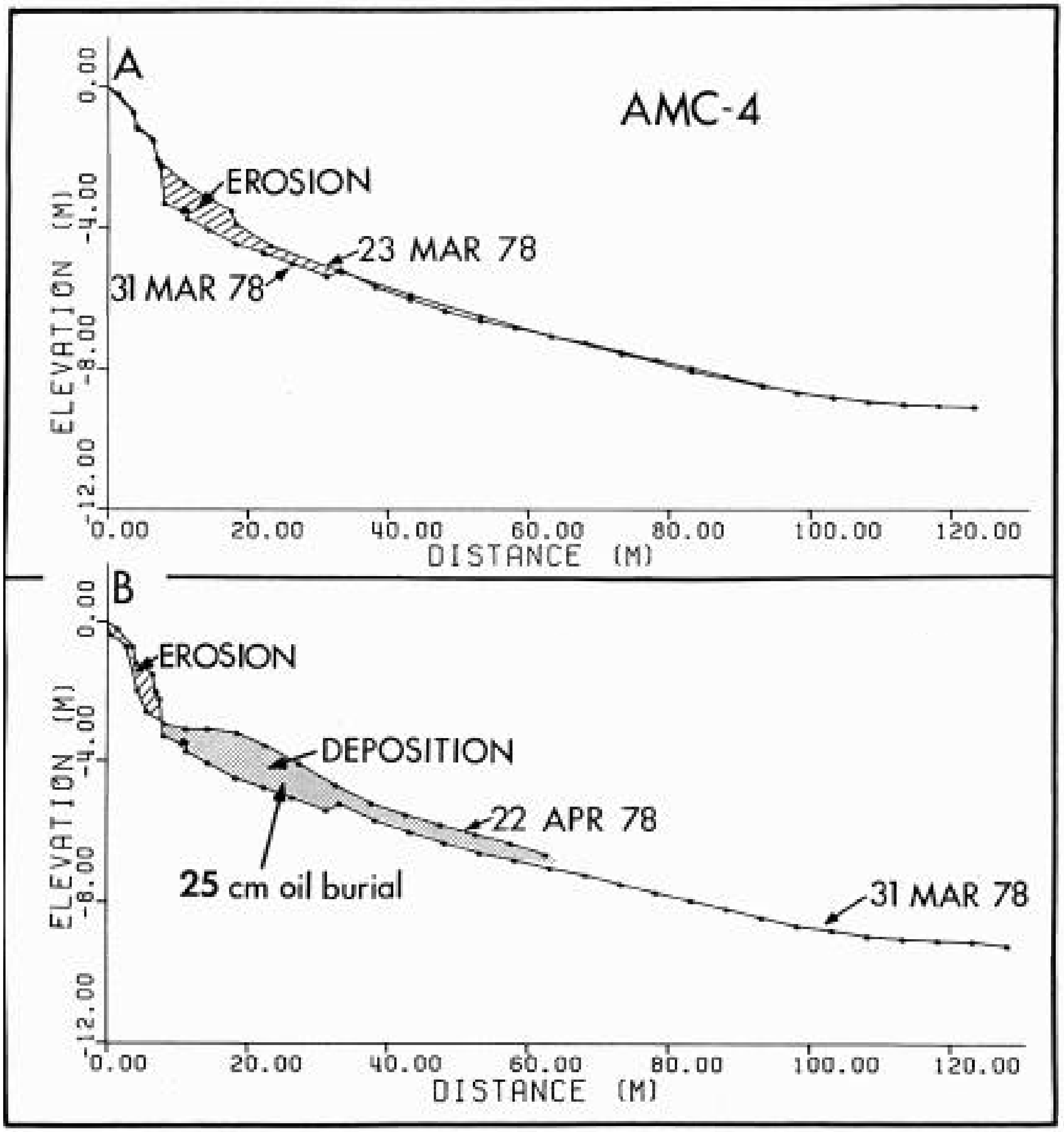


Figure 3-11. Burial of oil as result of beach-profile changes on an oiled sand beach at the *Amoco Cadiz* spill site (Brittany, France). The upper diagram shows loss of sand from the upper part of the profile in late March. Deposition of new sand on the beach between 31 March and 22 April resulted in deep (25 cm) oil burial. The beach continued to accrete, and the oiled zone was buried by 82 cm of sand by November. (After Gundlach and Hayes, 1978.)

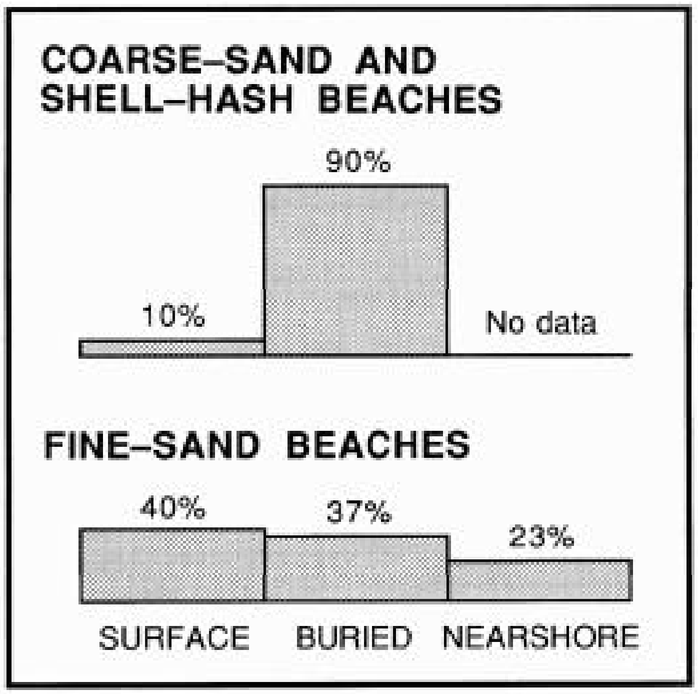


Figure 3-12. Oil occurrence on coarse-sand/shell-hash versus fine-grained sand beaches in South Texas as result of *Ixtoc 1* spill. Note predominance of buried oil in the coarser-grained beaches Based on examination of 16 stations on 3-6 September 1979. (After Gundlach et al., 1981.)

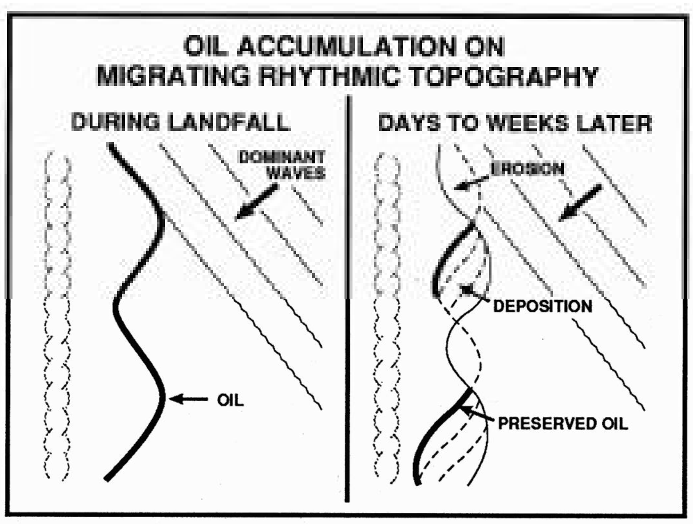


Figure 3-13. Process of oil burial on a beach containing alongshore migrating rhythmic topography. This process was observed at both the *Metula* and *Exxon Valdez* oil-spill sites. (After Hayes and Gundlach, 1975.)

The behavior and short-term impacts of oil on coarse-grained sand beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will concentrate in a band along the high-tide line
- Under heavy accumulations, oil can cover the entire intertidal zone, although the oil will be lifted off the lower part of the beach with the rising tide
- Large amounts of oil can accumulate in the berm runnel where it is unable to drain off the beach at low tide
- Penetration of oil into coarse-grained sand can reach 25 cm
- Burial of oiled layers by clean sand within the first few weeks after the spill can be rapid, and up to 60 cm or more
- Burial over 1 m is possible if the oil is deposited at the beginning of an accretionary period
- Persistence of deeply buried oil could be long, depending upon the season of year and beach cycle
- Biological impacts include temporary declines in infaunal populations, which can also affect feeding shorebirds
- The sediment can be very soft, making vehicular access difficult

On sheltered beaches:

- More of the beachface can be covered because it is narrow
- Oil penetration will be less where the sediments are finer and more poorly sorted
- Depending on the degree of exposure to any waves, oil persistence can increase to months to years
- Burial by clean sand is still significant but less than exposed beaches
- Asphalt pavements can form under heavy accumulations; pavements will change nature and stability of the substrate and thus its biological utilization

Gravel Beaches

Introduction

Gravel beaches are less well studied than sand beaches and present special problems with regard to the behavior and fate of spilled oil that reaches them. The term gravel refers to a wide range of grain sizes and is further divided into classes as follows:

Class	Size Range
granule	2 - 4 mm
pebble	4 - 64 mm
cobble	64-256 mm
boulder	> 256 mm

Figure 3-14 is a visual estimate chart which shows the gravel classes. The term "rock" is commonly used at spills to refer to gravel, but we recommend that this term be restricted to bedrock or possibly large rubble at the base of cliffs.

Gravel beaches are most common along two types of coastlines–glaciated coasts and rocky, mountainous coasts. Coasts now subject to glaciation, such as the south-central coast of Alaska, typically have gravel beaches along up to 50 percent of their lengths. Areas subject to Pleistocene glaciation, including much of the temperate to subpolar regime of the Northern Hemisphere, also have abundant gravel beaches where the relict glacial deposits are eroding. Erosion of rocky, mountainous coasts, such as those that occur on parts of the outer coasts of Washington, Oregon, and California, also tends to produce gravel beaches.

Gravel beaches are complex features. Research on sediment transport on gravel beaches is quite limited in comparison with work on sand beaches. Sediment transport patterns on gravel beaches are different from those of sand beaches, with gravel being transported landward during storms, forming high berms called *storm berms*, rather than being eroded and deposited offshore. Gravel beaches occur in a very wide range of energy regimes, with complex geologic and topographic settings. Bedrock headlands are usually present, separating isolated gravel beaches. Some gravel beaches are located on straight, open shorelines where they are constantly subjected to large waves. However, many gravel beaches are exposed to significant

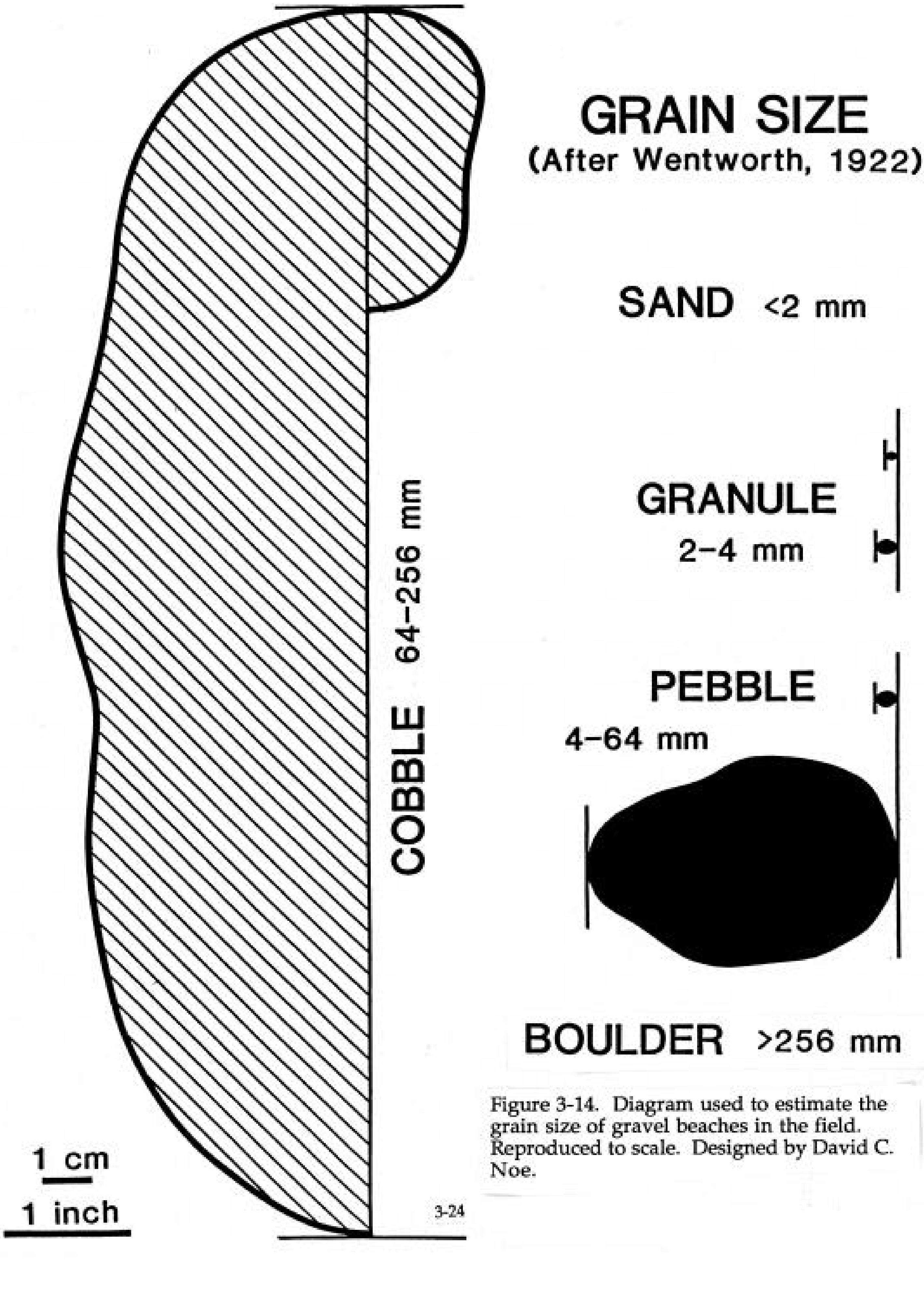


Figure 3-14. Diagram used to estimate the grain size of gravel beaches in the field. Reproduced to scale. Designed by David C. Noe.

wave activity only seasonally, and then only when waves approach from a specific direction. Under these conditions, 1-2 seasons might pass between mobilizing storm events.

Pure Gravel Beaches

Controls of Nature of Gravel Beaches. The internal character of waves is one of the most important determinants of the nature of gravel beaches. Hayes et al. (1991) classified gravel beaches as *reflective* or *dissipative*, according to the types of predominant wave conditions (Fig. 3-15). Reflective waves break close to the beach and are characterized by surging breakers with high run-up and minimum set-up. Reflective gravel beaches show clear evidence of size and shape sorting on steep beachfaces, have multiple cuspate berms, and a narrow directional width of incoming wave angle, which is always shore-normal. Oil deposited on reflective gravel beaches could be buried under the developing berms. In contrast, dissipative waves typically break tens of meters seaward of the beach and dissipate their energy before reaching it. Gravel beaches we classify as dissipate show strong evidence of longshore transport, frequent shifts in wave conditions, and limited swell effects. Where beaches are host to both wave conditions, dissipative waves are more common during storms, with reflective waves more common during calmer periods (Fig. 3-15). During dissipative storm wave conditions, spilled oil may be carried high into the storm berm environment and penetrate into the coarse material above the elevation of normal reworking.

Morphology and Sediments. Figure 3-16 shows a typical profile for a gravel beach exposed to large waves. Note the large, multiple pebble and cobble berms at the upper part of the profile and the eroded, wave-cut platform of the lower part, which is covered with boulders up to a meter in diameter. The grain-size distribution shows the very coarsest material on the outer platform and finer material on the depositional berms, with the storm berm being slightly coarser than the lower-level berms accreted on its seaward face.

On some gravel beaches, a stable armor of coarse material develops over the surface of the middle and lower portions of the beachface (Michel and Hayes, 1991), as illustrated in Figures 3-17 and 18. On a beach which typically has constantly changing current velocities, threshold transport conditions for different particle sizes are frequently achieved. Also, smaller particles are shielded by larger particles.

These factors combine to allow intermediate-sized particles to be removed and a coarse armor to develop over the finer particles, as shown in Figure 3-17. Once armoring is achieved on gravel bars in rivers, a process known as *structural strengthening* occurs (White and Day, 1979), such that a stronger current is required to transport the material available (at least one-fourth greater). It is assumed that the same type of structural strengthening occurs on armored beaches.

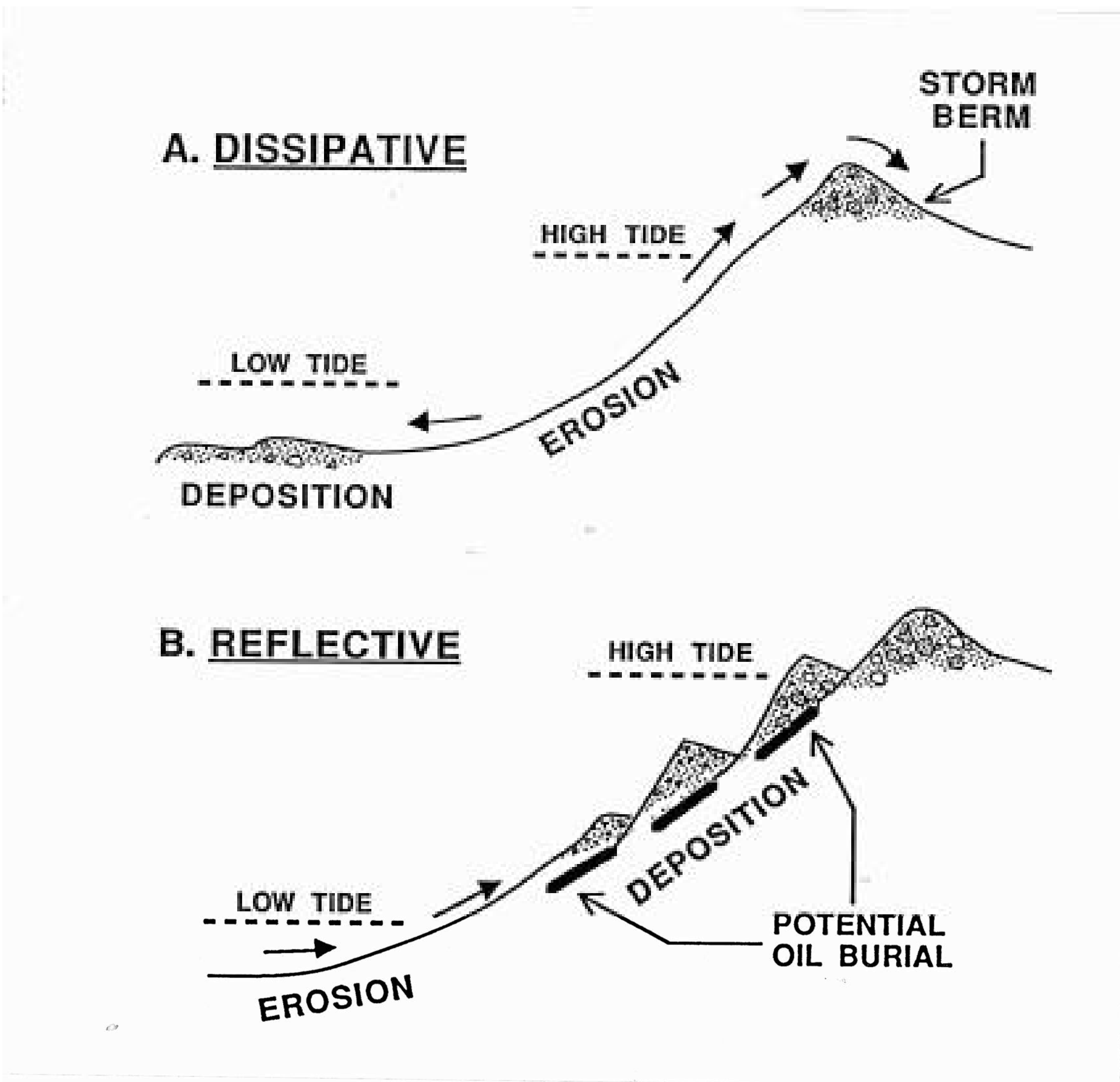


Figure 3-15. Examples of types of changes in morphology at the same gravel beach during dissipative and reflective wave conditions. Dissipative waves prevail during storms, and reflective waves are present during calmer periods on gravel beaches of this type. Note sites of potential oil burial at base of post-storm, constructional berms, a process observed at the *Exxon Valdez* spill site. (From Hayes et al., 1991; Fig. 2.)

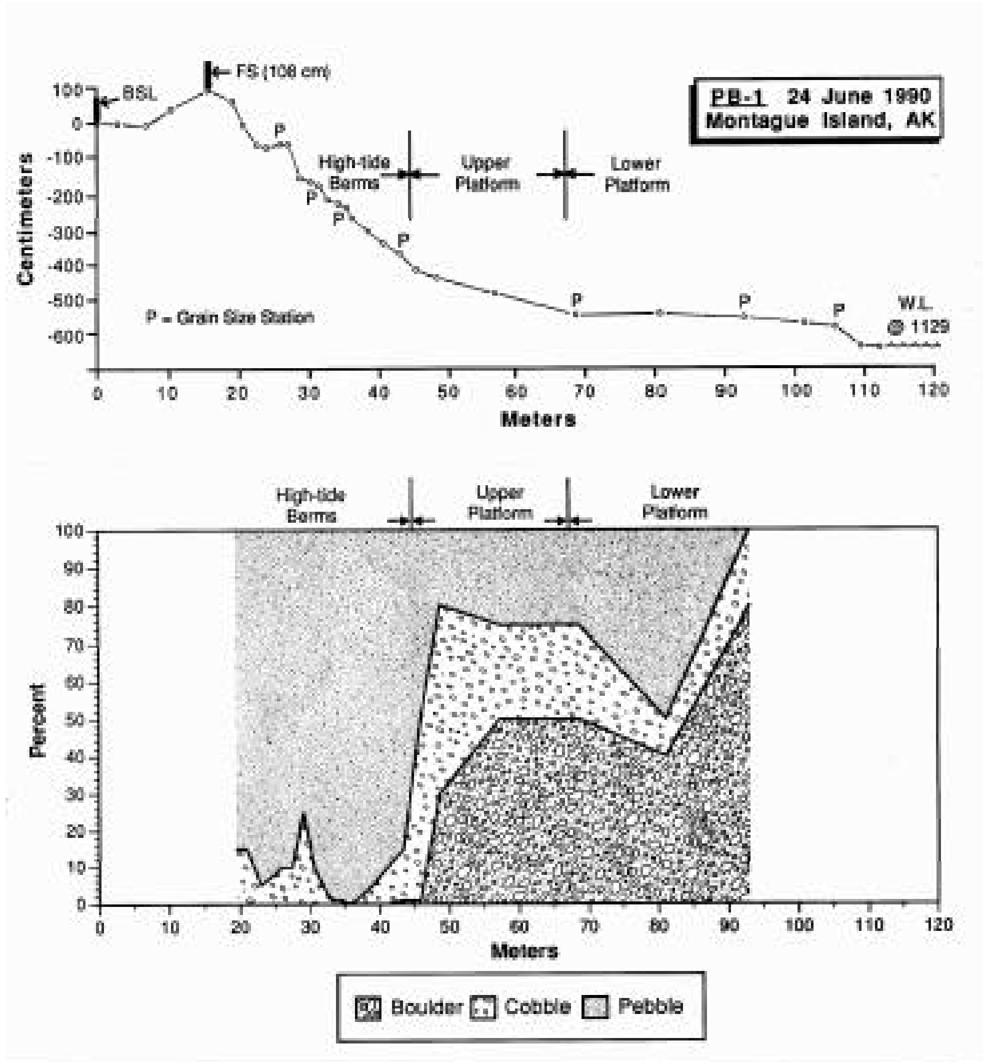


Figure 3-16. Beach profile and distribution of surface sediments for profile PB-1, on the outer coast of Montague Island, Alaska. This profile, measured at low tide on 24 June 1990, is typical of exposed, high-energy gravel beaches in an eroding, retreating setting. This area, which was subject to more than three meters of uplift in the March 1964 earthquake, has readjusted rapidly because of the constant reworking of the beach by large waves. (From Hayes et al., 1991; Fig. 3.)

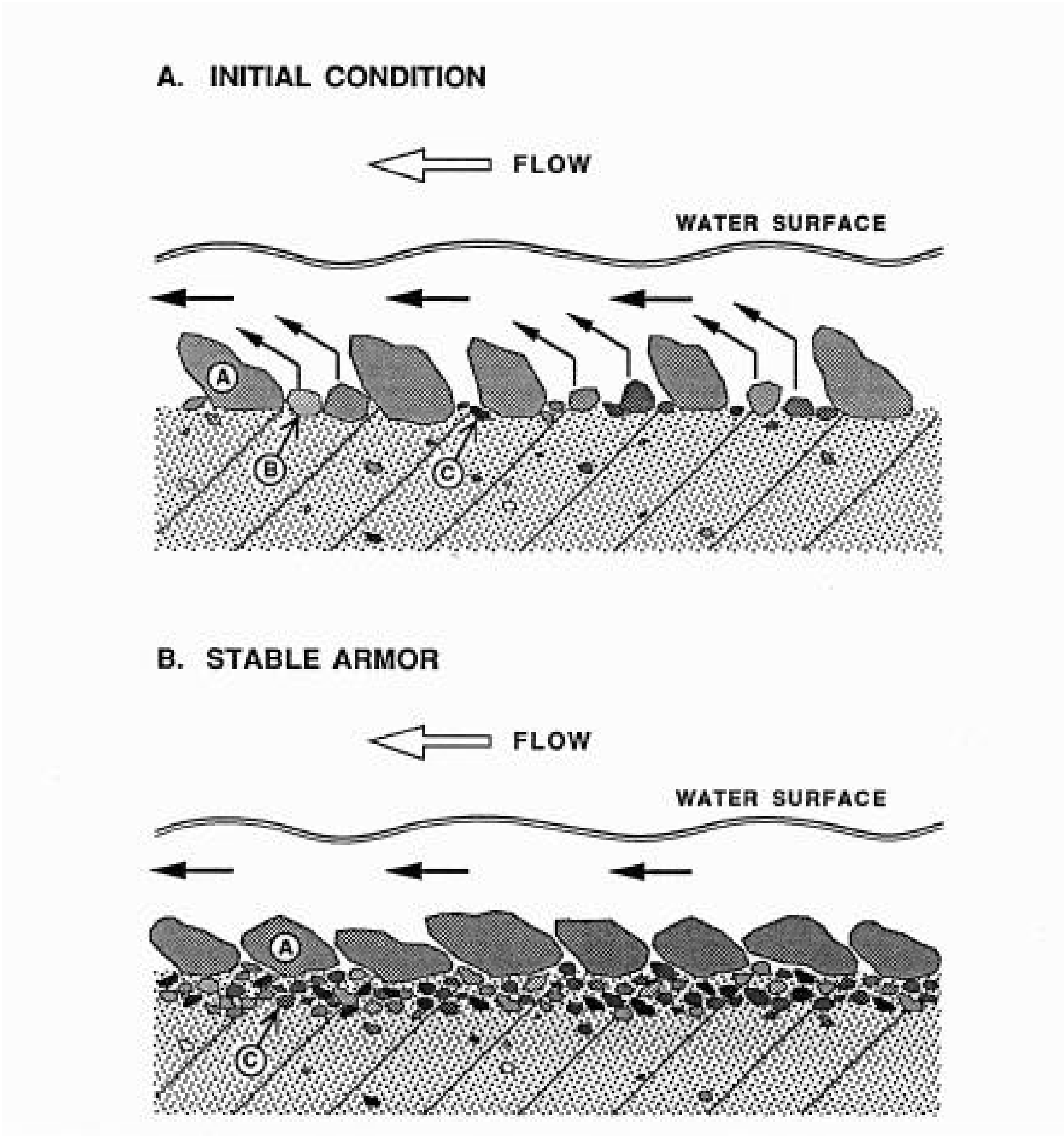


Figure 3-17. Process involved in the development of an armored surface of coarse material on a gravel beach. The particles of size A are too large to be removed by prevailing currents, those of size B are readily transportable, and those of size C are sheltered by the larger particles and are not picked up by the current. The C particles are on the order of 1 1/2 to 3 times smaller than the A particles. (From Hayes et al., 1991; Fig. 7.)

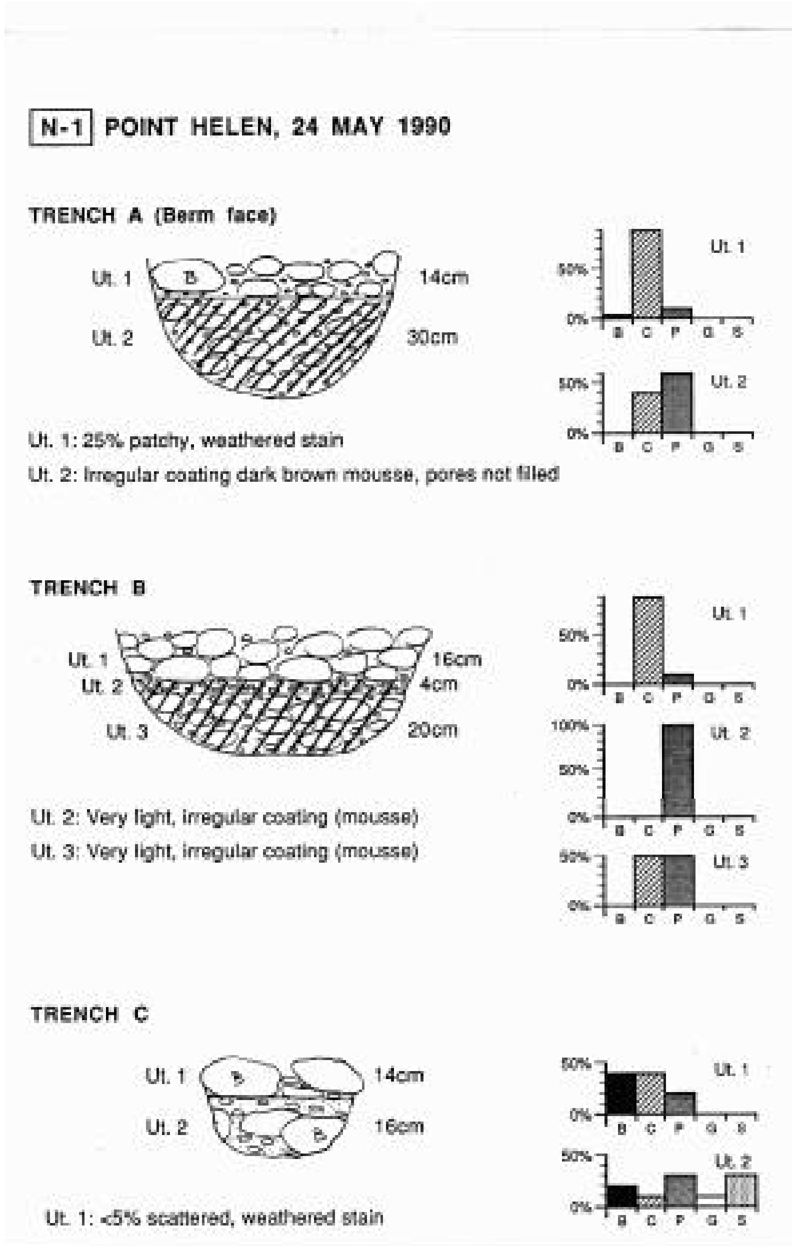


Figure 3-18. Examples of armoring on the beach at Point Helen, Prince William Sound, Alaska, on 24 May 1990. Oil from the *Exxon Valdez* spill occurred underneath the armor in trenches A and B. (From Hayes et al., 1991; Fig. 8.)

Many of the beaches in Alaska are armored, especially on the platforms. The trenches illustrated in Figure 3-18 for an armored beach oiled by the *Exxon Valdez* spill demonstrate how subsurface oil is protected below the coarse armor. The surface sediments, mostly cobbles, are clean, but the pebble-dominated subsurface sediments were still oiled, over a year after the spill. Oil beneath an armored surface would tend to remain for a longer period of time than oil buried on an unarmored beach, because of the higher velocities required to mobilize the armor. Thus, the stable armor shelters subsurface oil from natural removal. For example, on a well-armored Alaskan gravel beach, sediments at depths greater than 25 cm contained 10,000 to 18,000 ppm total petroleum hydrocarbons (TPH) in January 1991, nearly two years after the *Exxon Valdez* oil spill (Michel and Hayes, 1991).

Oil Behavior on Gravel Beaches. A number of special features of gravel beaches enhance oil accumulation and preservation during an oil spill. The major ones are:

1) *They have high porosity and permeability that allow deep penetration from the surface.* At the *Urquiola* spill, fresh oil readily penetrated up to 65 cm in gravel beaches (Fig. 3-7). At the *Exxon Valdez* spill, the oil had formed a thick mousse which piled up heavily on the beaches at first, when the cold temperatures kept the viscosity high. However, as the days warmed, the oil, which had been pooled in places on the surface, literally melted into the beach. The deepest penetration observed was 125 cm along the banks of a small stream, although the average depth of penetration was around 50 cm. After such oil penetration, the issue becomes one of predicting if and when natural processes will remove the subsurface oil.

2) *They have a high potential for oil burial by accretional features.* Gravel tends to be highly mobilized during peak and waning periods of storm activity. The finer gravel classes, such as granules, pebbles, and small cobbles, are readily moved by normal wave activity. The gravel may be moved onto the beach, in the form of berms or swash bars (Figs. 3-15B and 19A), or parallel to the beach, in the form of rhythmic topography (Fig. 3-19B). One of the biggest cleanup issues of the second year of the *Exxon Valdez* spill was what to do about deeply buried oil on the Barren Islands, where large seabird nesting colonies occur. Berm accretion had buried a layer of oil over a meter deep in a gravel beach hundreds of meters long. Later erosion would surely release the oil, but no one could be sure when and under what conditions.

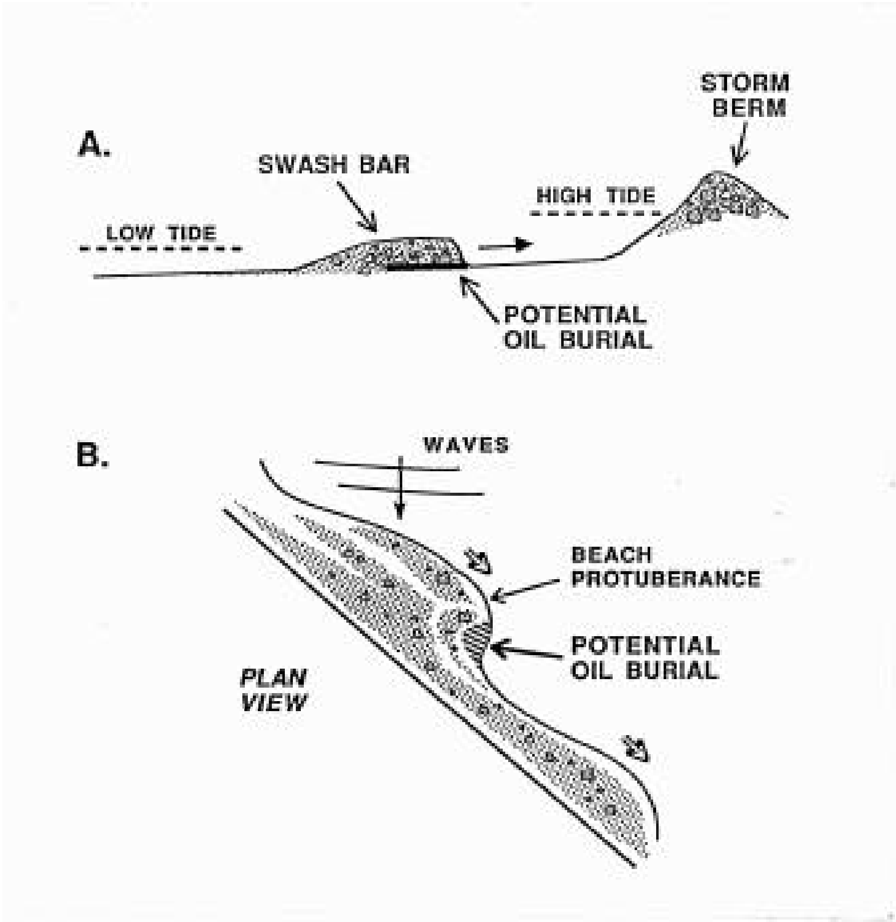


Figure 3-19. Two types of potential oil burial at permanently dissipative gravel beaches. In both examples, a mass of sediment in motion buries oil deposited at an earlier time. Oil burial by migrating rhythmic topography (B) was observed at the *Metula* spill site, and oil burial by migrating swash bars (A) was observed at the *Exxon Valdez* spill site. (From Hayes et al., 1991; Fig. 1.)

3) *The formation of asphalt pavements in sheltered areas is likely where accumulations are heavy.* Shorelines with gravel beaches tend to be irregular in outline, and sheltering from wave action is common. Even on generally exposed beaches, there can be microenvironments where oil tends to accumulate, persist, and form pavements: in the lee of larger boulders, on tombolos, and in the wave shadow of exposed headlands. At the *Arrow* spill site in Chedabucto Bay, Nova

Scotia, stranded bunker C oil remained as scattered patches of pavement 20 years later (David Kennedy, pers. comm.). During the 1991 multi-agency shoreline survey of the *Exxon Valdez* spill site, small amounts of asphalt pavement could be found on nearly every gravel beach in Prince William Sound that had been heavily oiled.

Because of these factors, gravel beaches pose very difficult cleanup problems. The rate of replenishment of gravel is usually very slow, and therefore cleanup by gravel removal can increase beach and cliff erosion where it is already a problem. Owens (1971) plotted multiple beach profiles at sites in Chedabucto Bay (the *Arrow* spill) where machinery was used to excavate oiled layers in gravel beaches over 1.5 m deep. He showed that, on beaches of limited sediment supply, removal of sediment caused erosion which was not replenished before the beginning of winter storms.

Mixed Sand and Gravel Beaches

As might be expected, mixed sand and gravel beaches have properties of both sand and pure gravel beaches. Because of the mixed sediment sizes, there can be distinct zones of sand, pebbles, or cobbles. For example, the berm is frequently composed of pebbles, surficial patches or stringers of sand can develop on the middle beachface, and cobbles usually dominate the lower beachface. The sand fraction can be quite mobile, and oil behavior is much like on a sand beach if the sand fraction exceeds about 40 percent.

Mixed sand and gravel beaches are irregular in outline, with rocky points or eroding cliffs forming headlands which provide the gravel clasts. Thus, the wave angle can be highly variable and rhythmic topography is common, with the associated potential for burial of oil by alongshore sediment movement. The gravel component can range widely in size and mobility, from highly mobile pebbles which form multiple berms, to large cobbles and boulders, which have very low sediment mobility and form a stable substrate over which the finer materials migrate.

Exposure of mixed sand and gravel beaches to significant wave activity can be episodic, particularly in places like Puget Sound where narrow channels and complex local topography limit fetch and wave height. Persistence of oil on these more sheltered beaches will be higher and natural removal processes will be less effective.

Because of sediment mobility and dessication, biological communities in mixed sand and gravel beaches are usually depauperate. The lower intertidal zone has the most epifauna (on the larger cobbles and boulders) and infauna.

The degree of oil penetration in mixed beaches is less than in gravel beaches, because the finer fractions fill the spaces between the gravel to some degree, although this is highly variable. Burial of oil is more likely on mixed beaches, and this oil can remain buried for long periods, up to years. One of the best examples of oil persistence in mixed beaches was observed at the *Metula* spill, which occurred in 1974 in the Strait of Magellan (Hayes and Gundlach, 1975; Blount, 1978; Gundlach et al., 1982; Owens et al., 1987). The majority of the shoreline impacted by the *Metula* consisted of mixed sand and gravel beaches, including a wide range of grain sizes and wave exposure. There was no cleanup of any shoreline.

Table 3-1 summarizes the observations made 1-2 years and then 6.5 years post-spill at selected locations at the *Metula* spill site. Within 1-2 years after the spill, **exposed beaches** still retained oil in two areas:

1) A band of both surface and subsurface oil along the upper beachface and above the highest berm crest

2) A layer of asphalted sediments on the low-tide terrace

The middle section of the beachface was free of oil on all exposed beaches. The subsurface oil remained soft and mousse-like in consistency. On the low-tide terrace, thick asphalted sediments ranged in width from 10-100 m. By 6.5 years, oil along the upper beachface had been reduced to a few layers, and oil on the low-tide terrace had been eroded from all but two stations, which had high currents but low wave activity. Figure 3-20 shows comparative profiles of a heavily oiled, mixed sand and gravel beach, where oil remained on the upper beachface. After 12 years, pavements 0.5 - 1 m in width and 50 to 100 m in length remained on the highest parts of the beaches. The consistency of the pavements ranged from soft to hard.

The persistence of oil on **sheltered** mixed sand and gravel beaches at the *Metula* site was much different. One to two years after the spill, field teams observed that:

1) Extensive pavements of asphalted sediments (up to 100 m wide and 700 m long) extended from the high-tide line to the toe of the beach

Table 3-1. Summary of observations at stations revisited during the 1981 survey of the *Metula* spill site. Oil was most prevalent at stations 3, 4, and 6—all located along the more sheltered First Narrows area. (From Gundlach et al., 1982.)

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

*Annual data not available.

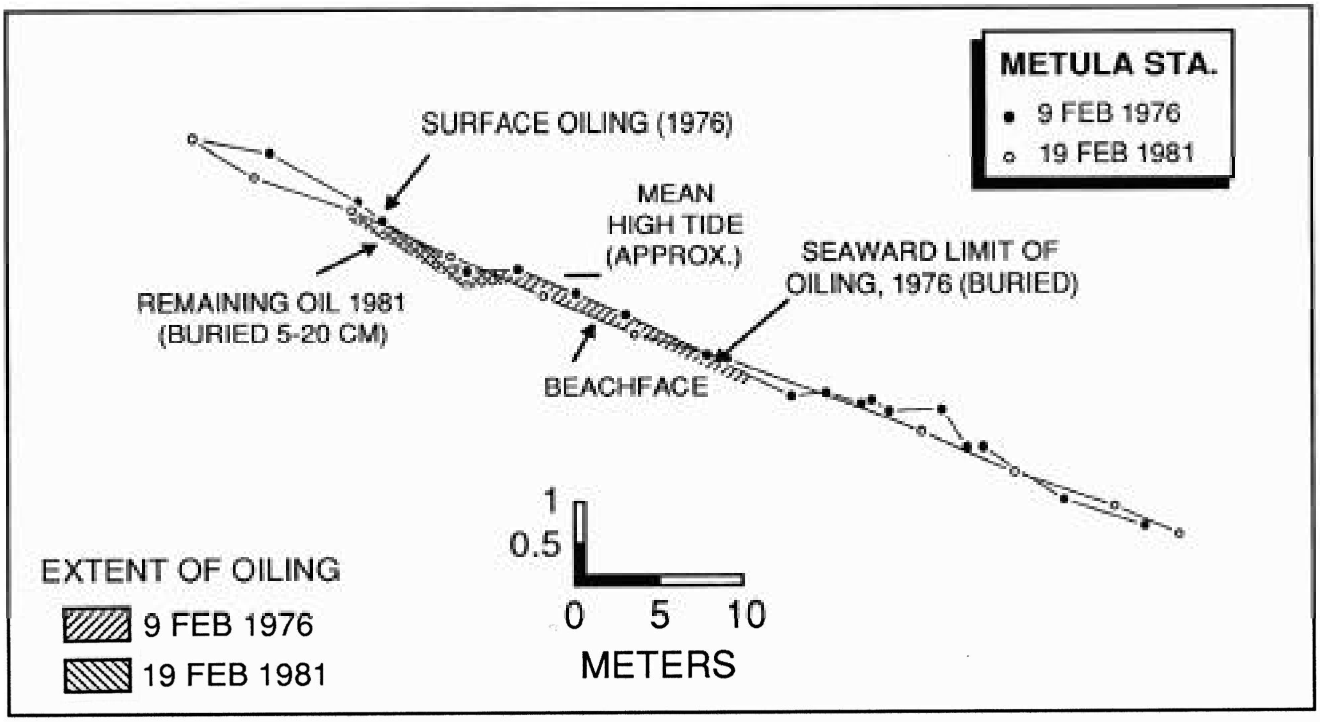


Figure 3-20. Changes in the oil distribution on a sand and gravel beach at the *Metula* spill site between 1976 and 1981 (Strait of Magellan, Chile). The surface oil present in 1976 was buried by 1981. Wave action had reworked much of the middle beachface area, removing the subsurface oil from that zone. However, 6.2 m of the original 19 m zone of oiled-sediment layers remained in place, seven years after the spill. (After Gundlach et al., 1982; Fig. 3A.)

2) Discontinuous bands and pieces of asphalted sediments were scattered throughout the intertidal zone

3) Most of the oil remained on the surface

By 6.5 years later, the extensive pavements showed only minor evidence of erosion along the upper edge of the pavement. After 12 years, there was still little change. Owens et al. (1987) reported that, at the most heavily oiled and sheltered site:

> "...oil is present: (1) in very large volumes (more than 100 m^3 in total); (2) over the entire area, which includes marsh, sheltered beach and exposed beach environments; (3) in all sections of the beach from the low-water level to the spring high-water level; and (4) generally as an apparently fresh deposit below a weathered surface crust."

The behavior and short-term impacts of oil on mixed sand and gravel beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will be deposited along and above the high-tide swash
- Large spills will spread across the entire intertidal area
- Oil penetration into the beach sediments may be up to 50 cm
- Burial of oil may be deep at and above the high-tide berm, where oil tends to persist
- Oil can be stranded on low-tide terraces composed of gravel, particularly if the oil is weathered or emulsified

On sheltered beaches:

- Pavements are likely to form wherever heavy accumulations of oil can fill the voids between the sediments
- Once formed, these pavements are very stable and can persist for many years
- Any oil stranded above the high-tide line will be highly persistant

Tidal Flats

Intertidal flats are deposits of sand and/or mud of very low slope that are exposed at low tide. The width of the flat is dependent on the tidal range and sediment supply; very wide flats are found mostly in macrotidal (TR > 4 m) areas. Tidal flats occur along shorelines sheltered from direct attack by large waves, although highly mobile sand shoals are common at the mouths of inlets. Thus, compared to beaches, tidal flats have slow deposition and erosion patterns.

Origin and Sedimentation Patterns

Much of the original work on the sedimentology of tidal flats was done on the shoreline of the North Sea, first by Van Straaten in the Wadden Sea, The Netherlands, and then by Reineck and colleagues on the tidal flats of Germany. Van Straaten published several summary articles (1951; 1954), and Reineck's work is summarized by Reineck and Singh (1975) and several later papers.

Through a series of detailed studies, van Straaten determined that the Wadden Sea can be subdivided into three distinct environments: the <u>marsh</u> (above mean high water level), the <u>tidal flat</u> (intertidal zone), and the <u>tide channel</u> (below mean low water level). He further subdivided the tidal flat in <u>high flats</u> (between mean high water and half tide levels) and <u>low flats</u> (between mean half tide and low water levels). The sediments of the high flats are intensely bioturbared, whereas those of the lower flats contain mostly physical sedimentary structures, such as ripple marks. These environments are illustrated in Figure 3-21, which indicates that the main trends in grain-size distribution in the Wadden Sea show a systematic decrease of mean size of sand and silt particles and an increase in clay content from the tidal inlets toward the estuary shores. The coarsest sediments are thus found on the bottom of the largest tidal inlets and the finest on the highest reaches of the tidal flats. The same pattern occurs on many other coastlines of the world, for example the mesotidal components of the coasts of South Carolina/Georgia, Alaska, California, and Puget Sound.

The problem of why large quantities of mud accumulate on the upper reaches of the tidal flat is an interesting one. Van Straaten and Kuenen (1957) indicated that much of this mud is deposited at ebb just before water is drawn away. Postma (1967) proposed that a combination of <u>settling lag</u> and <u>scour lag</u> moves fine-grained

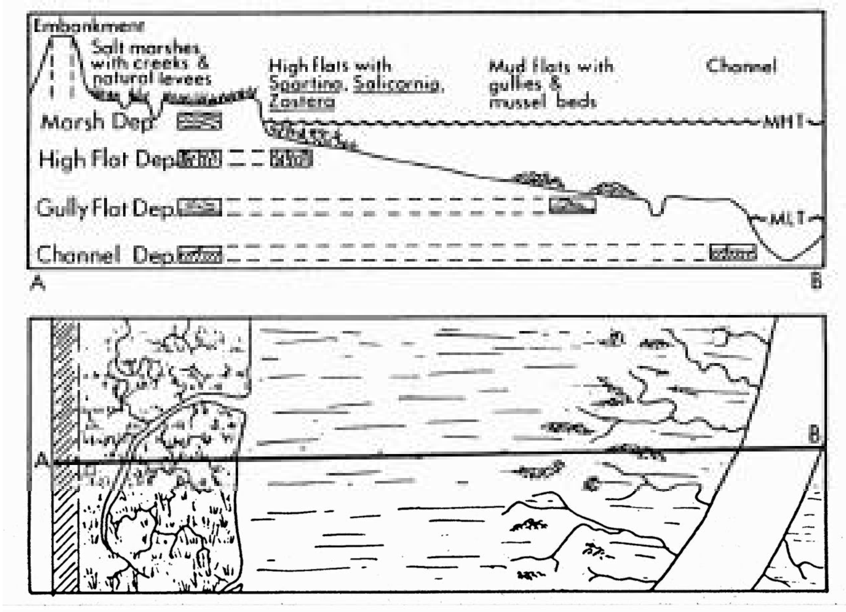


Figure 3-21. Sheltered tidal flat region of the Wadden Sea, The Netherlands. (After Van Straaten, 1951.)

sediments up into the estuary. These processes, which are shown diagrammatically in Figure 3-22, were described as follows by Nichols and Biggs (1985; p. 138):

> "*Settling lag effect*. The diagram ..(in Fig. 1-22).. shows the velocities with which different water masses move with the tides at each point along a section through a tidal inlet (left) to the shore (right). Although the tide at fixed points is assumed to be symmetrical, the distance-velocity curves are asymmetrical. A water mass moves in and out along one such curve. The tangent (P) represents the maximum current velocity in each point and meets each curve at a point attained by the water mass at half tide. The curves apply only to idealized average conditions, and scour lag is neglected.
>
> A particle at point 1 is taken into suspension by a flood current (water mass at A) of increasing velocity and starts to settle toward the bottom at point C, when the current still has a velocity equal to 2. While settling, the particle is carried farther inland by the still flooding currents and reaches the bottom at point 5 while the water has a velocity at point 4.

Scour lag effect. After the turn of the tide, the particle cannot be eroded by the same water mass (AA′) because this water parcel attains the required velocity later at a point beyond the particle toward the inlet. The sediment particle is therefore eroded by a more landward water mass (B′) and is transported toward the inlet to point B. At 7, it starts to drop out of suspension and reaches the bottom at point 9. During one tidal cycle, the particle has therefore been transported landward from point 1 to 9. After a number of these landward transport cycles, the particle may reach a point where it cannot be entrained by subsequent ebb flow currents because of the landward decrease of the average velocity of the tidal current (after Postma, 1967, and Van Straaten and Kuenen, 1957)."

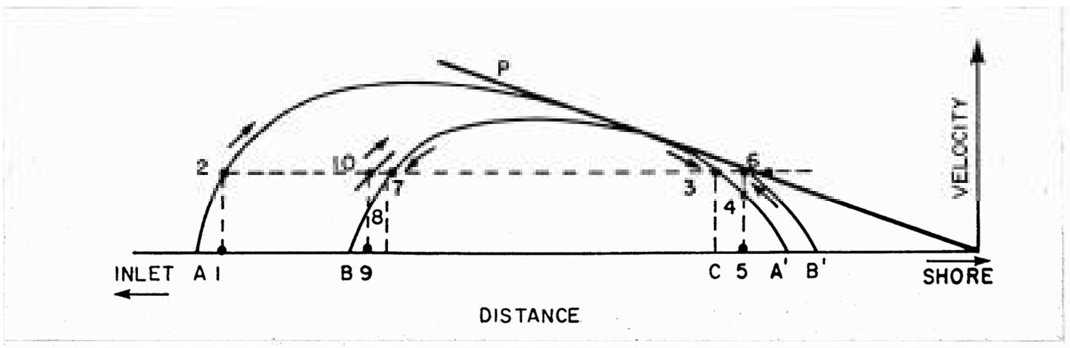


Figure 3-22. Diagram of the settling lag and scour lag effect in estuaries as described by Postma. (From Nichols and Biggs, 1985; Fig. 2-39.)

Eventually, the fine sediments reach the tidal flats.

Flocculation and aggregation of suspended silts and clays is another process that aids in the buildup of muddy sediments in estuaries (and ultimately on tidal flats). Examples of sizes and groups of flocculated particles are given in Figure 3-23.

In order for flocculation to occur, the suspended particles must be brought together (i.e., collide) and stay together (i.e., cohere). Collision is enhanced in waters with large volumes of suspended sediments, and the natural forces that tend to repluse fine particles from each other are destabilized by high concentrations of cations,

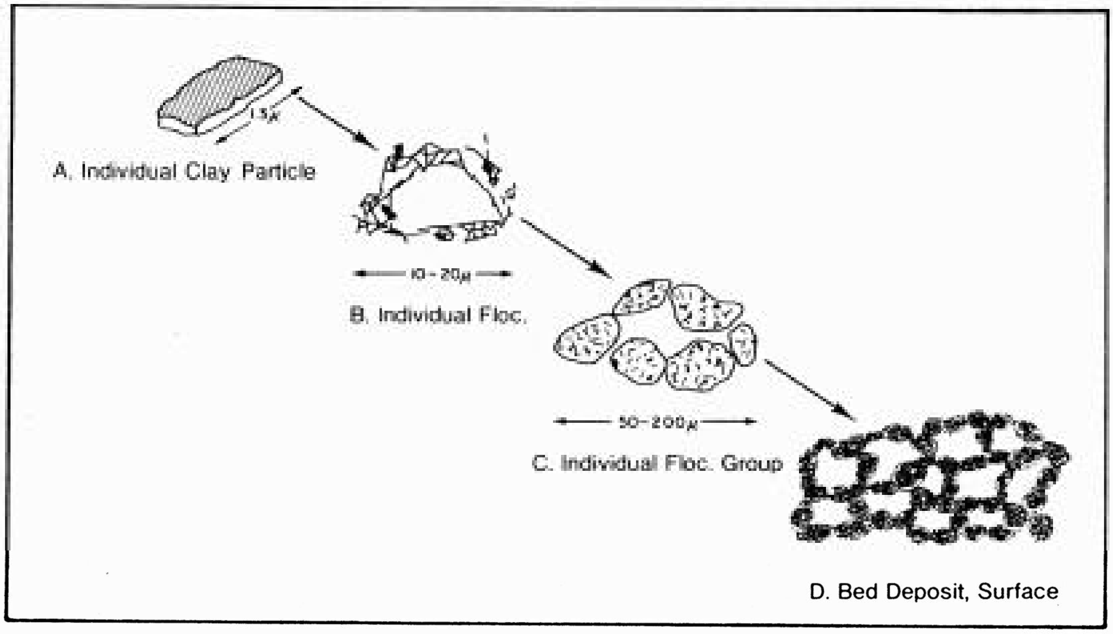


Figure 3-23. Schematic sequence of typical structures and size of flocculated fine sediments (flocs) and groups of flocs. (From Nichols and Biggs, 1985; Fig. 2-41.)

such as Ca++, Mg++, and Na+ (Nichols and Biggs, 1985). Both of these conditions are met in estuaries, where sediment-laden stream waters mix with the "salt wedge" of marine water that moves into the estuary on a rising tide.

Once the mud is deposited on a tidal flat, it tends to remain there because:

1) The mud dries out.
2) Burrowing organisms tend to stabilize the mud.
3) Diatoms move up through the mud and deposit slime.
4) Much higher velocities are required to <u>erode</u> consolidated mud than those at which it was <u>deposited</u>, as illustrated by the diagram in Figure 3-24.

In some instances, mud is trapped between plants on the flat. Another factor of prime importance to mud deposition is the super-abundance of the suspension-feeding organisms on the flats, such as oysters and clams. During the filtering process, these organisms compress the finely divided clay particles and bind them together in their intestines as fecal pellets. Another part of the suspended matter is

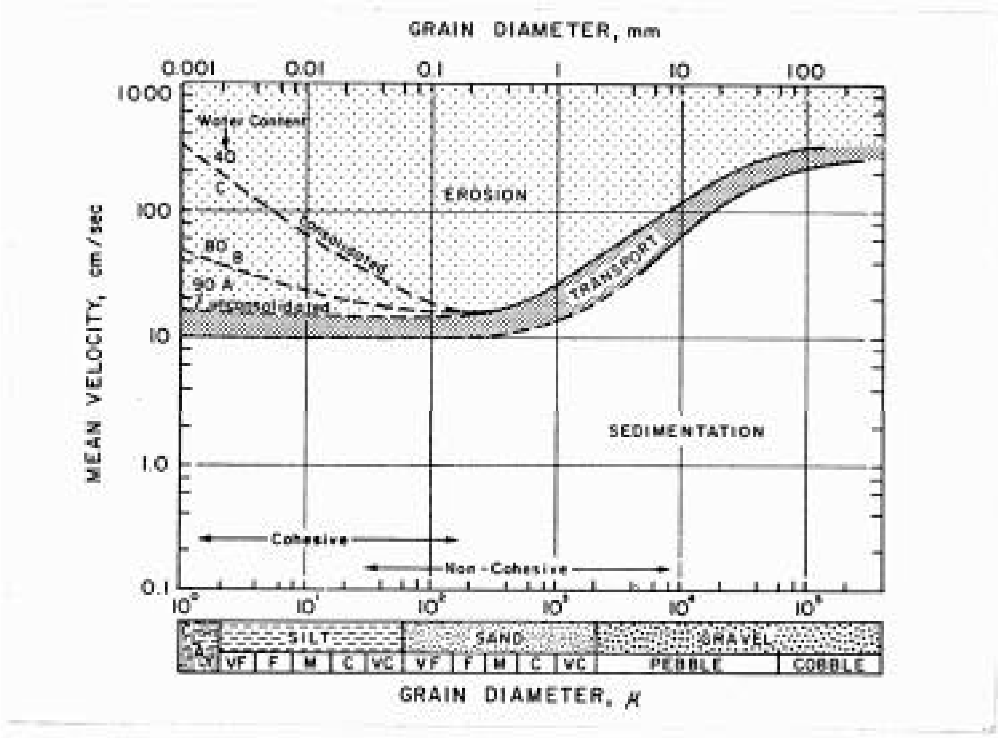


Figure 3-24. Sediment erosion, transport, and deposition regimes for mean current velocities versus grain size. Solid lines represent critical velocities required for erosion, transport, and deposition of bed sediment while dashed lines represent extrapolated trends. Lines A-C are critical velocities for various stages of consolidation represented by decreasing water content. Adapted from Hjulstrom (1939) and Postma (1967); by Nichols and Biggs (1985; Fig. 2-17).

coagulated in their gills and pushed back into the water as pseudo-feces. These feces and pseudo-feces are easily deposited, even in comparatively turbulent water (Van Straaten and Keunen, 1957). This process of mud accumulation is clearly evident around the oyster mounds on the tidal flats of the South Carolina coast (Hayes and Sexton, 1989).

For oil-spill planning, tidal flats are divided into two types: exposed and sheltered.

Exposed Tidal Flats

Exposed tidal flats can be characterized as follows:

- They are composed primarily of sand and mud (silt and clay), though in Alaska they can have a large gravel component

- The presence of sand indicates that tidal or wind-driven currents and waves are strong enough to mobilize the substrate
- They are always associated with another shoreline type on the landward side of the flat
- There may be low sand ridges slowly migrating over the flat surface
- The sediments are water-saturated, with only the topographically higher ridges and bedforms drying out during low tide
- The sediments are compact and may support pedestrian and vehicular traffic in some areas
- Biological utilization can be very high, with varying numbers of bivalves, macroinvertebrates, and polychaetes
- Birds utilize exposed flats as roosting and foraging areas

The behavior of oil on exposed tidal flats has been studied at several major spills. At the *Metula* site, oil slicks moved across wide flats (up to 10 km wide) and accumulated only at the landward edge of the flat (Blount, 1978). The oil remained on the surface, penetrating only a few centimeters, and there was no burial after 1.5 years. Because the wide flats attenuate nearly all the wave energy, the oil eventually formed into a thin pavement or crust which remained unchanged for 6.5 years. At the *Urquiola* spill, oil was observed to pass over the flats and accumulate on the adjoining beach. At low tide, heavy oil slicks covered the flat, but the rising tide would lift the oil off and push it across the flat. No long-term deposition of oil on the flats was observed, although the surface sediments were lightly stained early in the spill. Biological impacts were significant, with over 70 percent mortality of cockles. At the *Amoco Cadiz* spill, heavy oil slicks passed across the flats; oiled sediments occurred on the tidal flats only where cleanup crews had dug trenches and pits for oil collection. Where high densities of bivalves occupied the flats, there were mass mortalities.

The only spill where significant contamination of exposed tidal flats has been reported is along the Saudi Arabian coast where the Gulf oil spill innudated the shoreline for 500 km. The oil coverage on the tidal flats was nearly 100 percent, as of May 1991. This spill was unique in that onshore winds kept extremely large slicks piled up against the shoreline for months. Eventually, the oil adhered to the intertidal sediments. But, the oil did not penetrate the sediments very deeply; in most cases, the oil was less than 5 cm deep, with a thin surface oil crust (Michel, 1991). Also, the oil did not completely fill the pore spaces, a condition that tends to result in formation of asphalt pavements, which would slow natural removal rates. Instead, the oiled sandy sediments showed permeability to water, which should speed removal by flushing and weathering by degradation. The surface crust had been ripped up and flipped over in some places, indicating that the flats were being exposed to tidal current energy. Tidal currents draining off the wide flats were generating enough energy to lift the oil crust and mobilize the sediments, providing an important "self-cleansing" mechanism.

Based on observations at many spills, the behavior of oil on exposed tidal flats can be summarized as follows:

- Oil does not usually adhere to the surface of exposed tidal flats, but rather moves across the flat and accumulates at the high-tide line
- Heavy accumulations will cover the flat at low tide
- Oil does not penetrate the water-saturated sediments
- Biological impacts can be severe, primarily to infauna, thereby reducing food sources for birds and other predators

Sheltered Tidal Flats

Sheltered tidal flats can be characterized as follows:

- They are composed primarily of silt and clay
- The sediments are very soft and cannot support even light foot traffic
- Wave energy is very low, although there may be strong tidal currents active on parts of the flat and in channels across the flat
- They are usually fronted by marshes
- They have a dense and diverse infauna, which is highly utilized by birds

Sedimentation on sheltered tidal flats results from deposition of sediment from suspension, which occurs primarily during periods of slack high water. The upper tidal flat is a zone of higher rates of accumulation of finer-grained material due to "differential time of inundation and submergence ...during a tidal cycle, associated changes in bottom-current velocities of tidal currents during a tidal cycle (being therefore concentrated over the low-tidal flats), and the dominance of suspension processes near the time of high tide and slack water, which favors preservation of mud in high-tidal flats." (Klein, 1985). The processes of flocculation and scour/settling lag, described above, are also important in the partitioning of sediment sizes along sheltered tidal flats.

Sheltered tidal flats become contaminated by direct contact with oil slicks and by deposition of contaminated suspended sediments. During the *Amoco Cadiz* spill, large waves dispersed the oil into the water column, both as the oil exited the ship and when storm waves eroded the oil from exposed beaches. During the first three weeks, about 20,000 metric tons of oil were estimated to be incorporated into the water column (Gundlach et al., 1983). This oil sorbed onto suspended sediments which were then deposited onto sheltered tidal flats; oiled intertidal sediments were found in sheltered bays which never received any surface slicks. Oil removal and weathering rates were slowest in very fine-grained sediments.

Based on observations at many spills, the behavior of oil on sheltered tidal flats can be summarized as follows:

- Oil does not usually adhere to the surface of sheltered tidal flats, but rather moves across the flat and accumulates at the high-tide line
- Very heavy accumulations will cover the flat at low tide
- Oil will not penetrate the water-saturated sediments at all
- In areas of high suspended sediments, sorption of oil can result in contaminated sediments that can be deposited on the flats
- When sediments are contaminated, oil will persist for years
- Biological impacts can be severe

Sheltered Rocky Coasts

Sheltered rocky coasts encompass many types and sizes of substrates. Included in this general class are:

- Vertical bedrock cliffs, such as along fjords
- Wide, rocky ledges which may be strewn with boulders

- Rocky, rubble slopes which are formed by passive accumulation of sand to boulder-sized talus on bedrock slopes

The only common factors among these diverse shoreline types are a hard substrate and the absence of significant wave or tidal energy. Otherwise, there can be wide variations in the width of the intertidal zone and the degree of "permeability" of the rocky substrate. Because of the low wave energy, there is little sorting of sediments, so the substrate is a jumbled mix of grain sizes, from boulders to clay. This poorly sorted mixture usually does not allow deep penetration of oil into the subsurface. But, then, where is the "surface" on a shoreline with boulder- and cobble-sized rubble layer overlying an irregular bedrock platform with patches of muddy sand and granules?

Without substrate mobility, the hard, rocky surface can be heavily colonized by a rich epifaunal community in the mid to lower intertidal zone, including algae, mollusks, and snails. On steep, sheltered bedrock shores, the intertidal zone can be nearly vertical; zonation patterns for attached epifauna have sharp boundaries because of the lack of waves to smear the zones over a wider area. Tidal pool communities are uncommon and small. Concrete seawalls are the man-made equivalents of this shoreline type.

Oil tends to readily adhere to the dry rock surface, particularly along the high-tide line where there are little to no attached organisms and the rock dries for longer periods. During the *Exxon Valdez* spill, many miles of sheltered vertical bedrock shores were heavily oiled in this manner. Only infrequently did oiling of the mid to lower intertidal zone occur. It seems that oil did not adhere to the wetter, heavily colonized surface of the lower half of the intertidal zone, but rather the oil lifted off these surfaces with the rising tide.

On sheltered, *vertical rocky shores*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide, forming a distinct oil band

- The lower half of the rock face usually stays wet enough to prevent oil from adhering and remaining

- Heavy oils and weathered oils can cover with upper zone with little impacts to the rich biological communities of the lower zone

- Fresh oil and light refined products have high acute toxicities which can affect attached organisms after even short exposures

On sheltered, *bedrock ledges*, the intertidal zone can be very wide. The surface can be covered with a wide range of grain sizes, but the bedrock ledge is the dominant substrate type. There can be some evidence of sorting of the sediment veneer, especially at the high-tide line where a small mixed sand and gravel beach can form. But the frequency of wave action is very low, at the most 1-2 times per year. In very sheltered settings, the rock ledge can be covered by a thin layer of weathering residue that fills in the cracks and crevices on the uneven rock surface.

Oil stranding on this shoreline type can coat the surface and penetrate this surface residue. Oil penetration will be limited by the depth of the intact bedrock surface. But it should be noted that rock fractures can be 10-20 cm deep and are common sites of oil pooling and persistence. Figure 3-25 shows a sketch, profile, and grain-size cover for a typical sheltered rocky ledge in Alaska. Note that the surface is covered by a thick layer of angular debris. The oil on this shoreline eventually formed a patchy asphalt pavement covering the upper one-third of the ledge. This specific site was not cleaned, as part of a research program to monitor the effectiveness of different treatment techniques versus natural recovery. Without any cleanup, heavy patches of oil have remained and formed pavements three years post-spill. The oil coating on the rock surfaces has dried, started to crack, and has been reduced by about 50 percent in 2.5 years. However, oil in the rock crevices and below the surface boulders has not changed at all and remains relatively fresh.

The biological utilization of these rocky ledges can be very high, with dense growth of algae and associated epifauna. Tidal pools can be common, and there can be a rich underrock community. When heavily oiled, the lower intertidal areas can be covered by oil trapped in low areas and pools on the irregular rock surface during the falling tide. If the oil is weathered and sticky, it can eventually strand, penetrating into the small accumulations of sediments on the rock surface. Seldom have we seen oil adhering to bedrock on the lower intertidal zone; the surface stays too wet and the oil is lifted off with the rising tide.

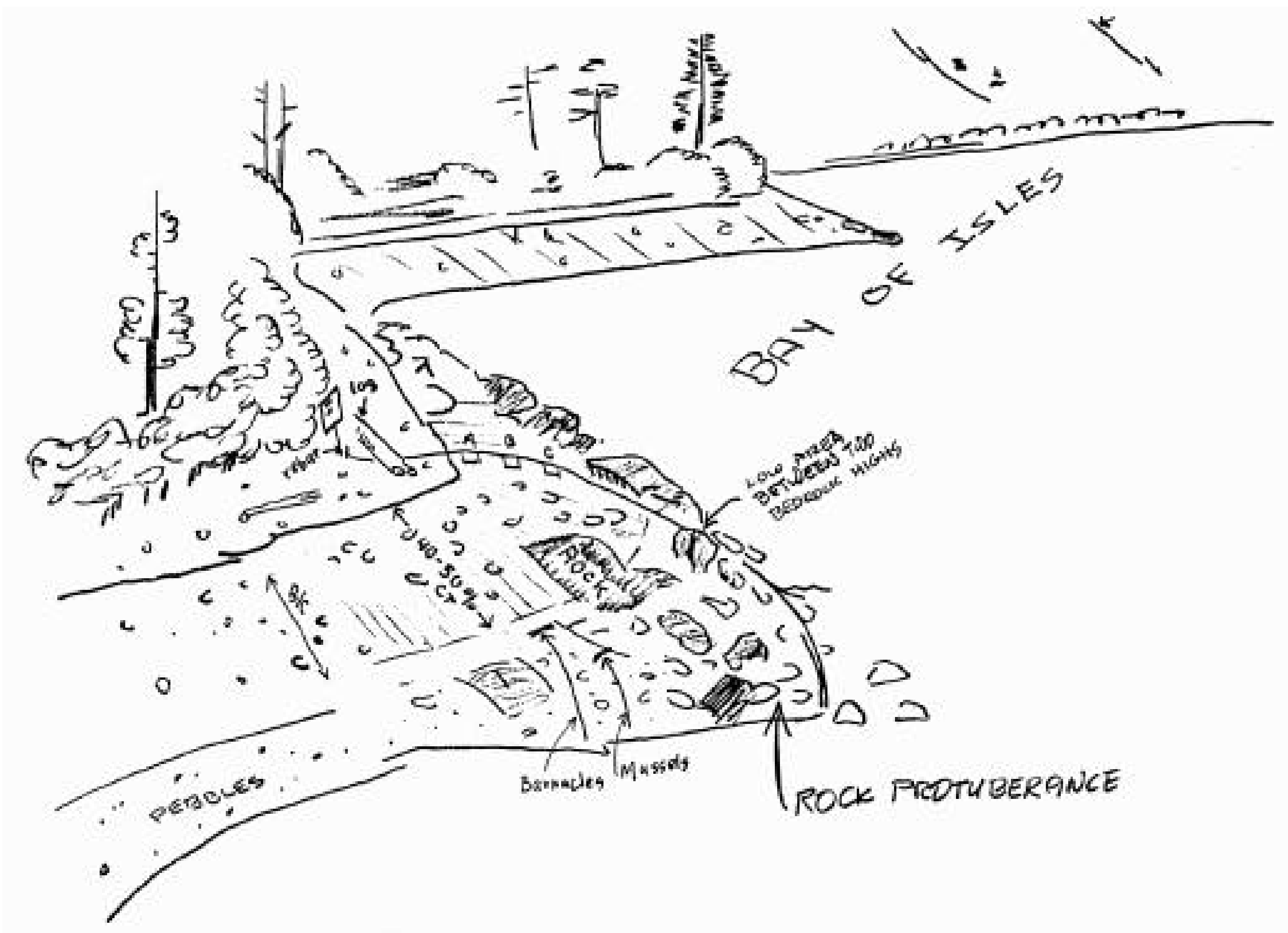


Figure 3-25. Example of a sheltered rocky ledge oiled during the *Exxon Valdez* spill, NOAA's station N-6 in the Bay of Isles, Prince William Sound. A) Beach sketch. A permanent topographic profile was run down a small draw between two bedrock highs. Note barnacle and mussel zones on lower half of the rock face.

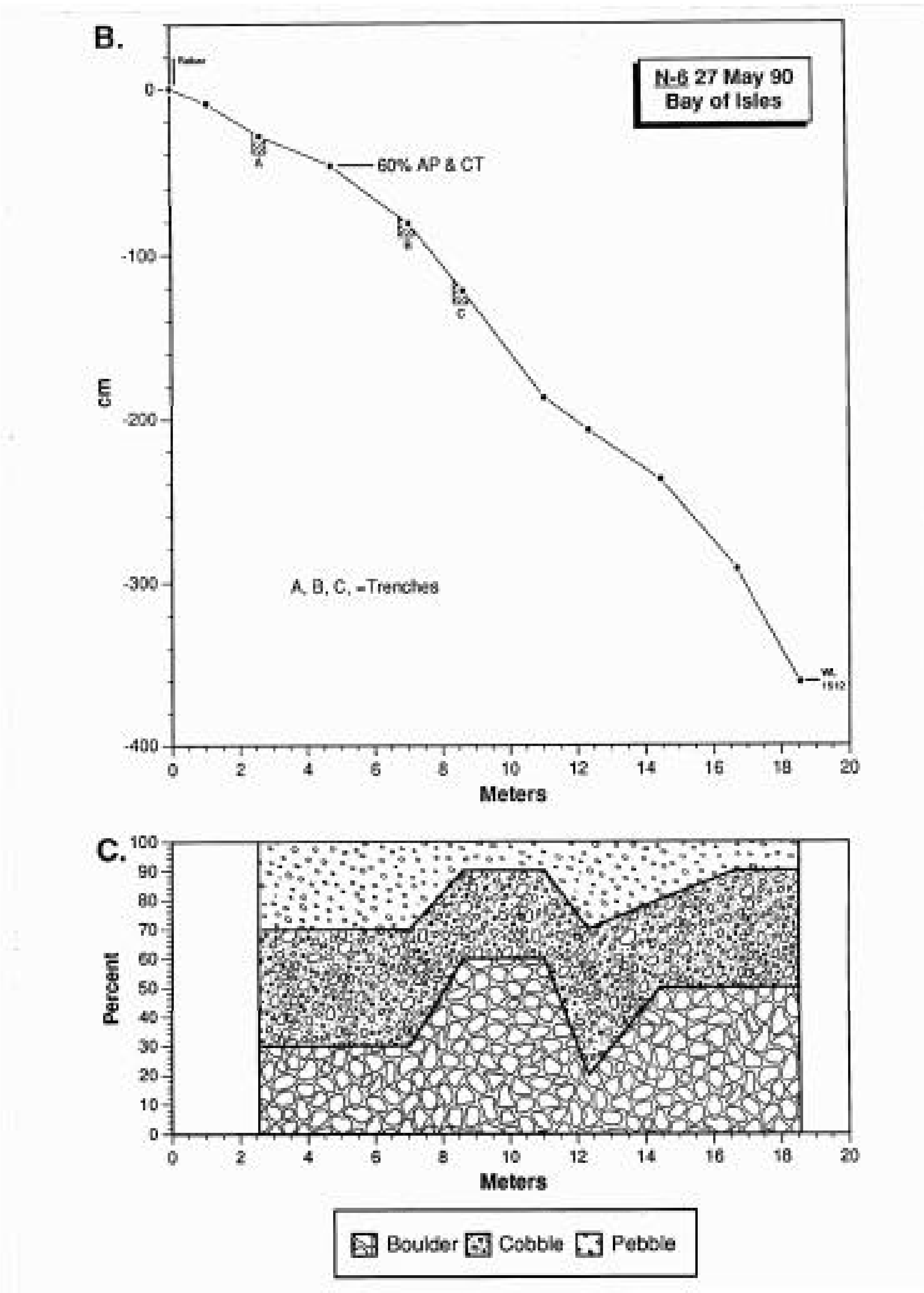


Figure 3-25. Continued. B) Topographic profile, illustrating the steepness of the profile. C) Surface sediment distribution pattern based on grain size estimates at eight of the survey points along the profile (circles shown in B). Note slight increase in size down the slope. This surficial debris is angular and poorly sorted, which indicates little transport by wave action.

On wide, *rocky ledges*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide, forming a distinct oil band
- If a beach is present, the oil will penetrate the sediments, with long-term persistence very likely
- Fractures in the bedrock surface are sites of oil pooling and persistence
- Even for wide ledges, the lower intertidal zone usually stays wet enough to prevent oil from adhering to the rock surface
- Heavy oils and weathered oils can persist on the lower intertidal zone by penetrating surficial sediments
- Fresh oil and light refined products have high acute toxicities which can affect attached organisms after even short exposures

Sheltered *rocky rubble slopes* have the greatest potential for long-term persistence of oil. These shoreline types are relatively steep and short. The bedrock surface can be covered with a thick veneer of poorly sorted materials, which can vary greatly in degree of permeability. Figure 3-26 shows a sketch, profile, and surface oil coverage for a rubble slope from Prince William Sound, which was set aside and never cleaned. Note that the oil stranded only on the upper zone, with 100 percent coverage in September 1989, six months after the spill. By September 1990, surface oiling had been reduced to a maximum of 30 percent coverage. Again, most of the oil on the undersides of the rubble remained.

Most of the time, the subsurface is very tightly packed and the oil penetrates only the top few centimeters. Without oil removal, pavements are formed. However, on this surface can be large boulders, and oil will be deposited in the open spaces between the boulders and at the base. It is nearly impossible to cleanup this oil and natural removal rates are extremely slow.

Another problem area on these rubble slopes is where they are covered with a loose assemblage of debris, which can be very permeable. Oil pooled on these slopes can penetrate deeply, up to 50 cm. At the site shown in Figure 3-26, fresh-looking oil remained at depths of 30 cm as of September 1991, 2.5 years later. Detailed chemical analysis of the oil showed that it had weathered very little.

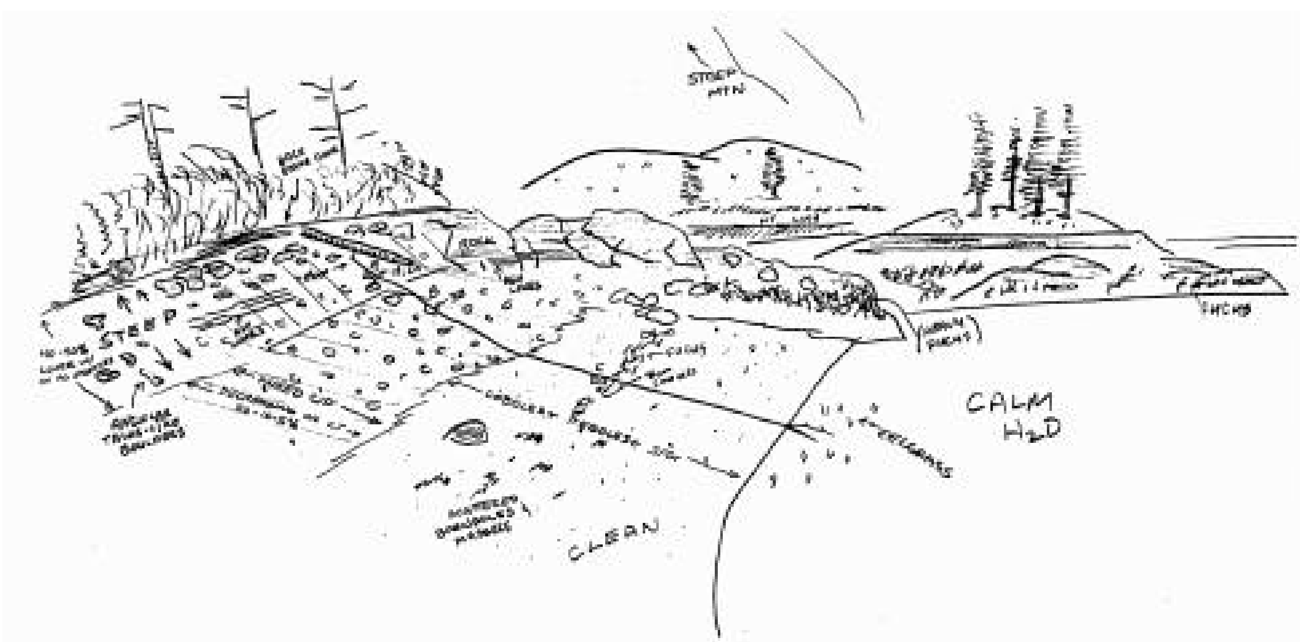


Figure 3-26. Example of a sheltered rubble slope that was oiled by the *Exxon Valdez* spill, NOAA's station N-13 in Herring Bay, Prince William Sound. A) Field sketch. The contrasting sediment types and slopes of the two subdivisions of the profile, angular talus-like material on the steep rubble slope and finer material on the flatter bay bottom, are evident. Oil cover as high as 50 percent was still present on the upper portion of the rubble slope on 27 May 1990, over one year after the spill.

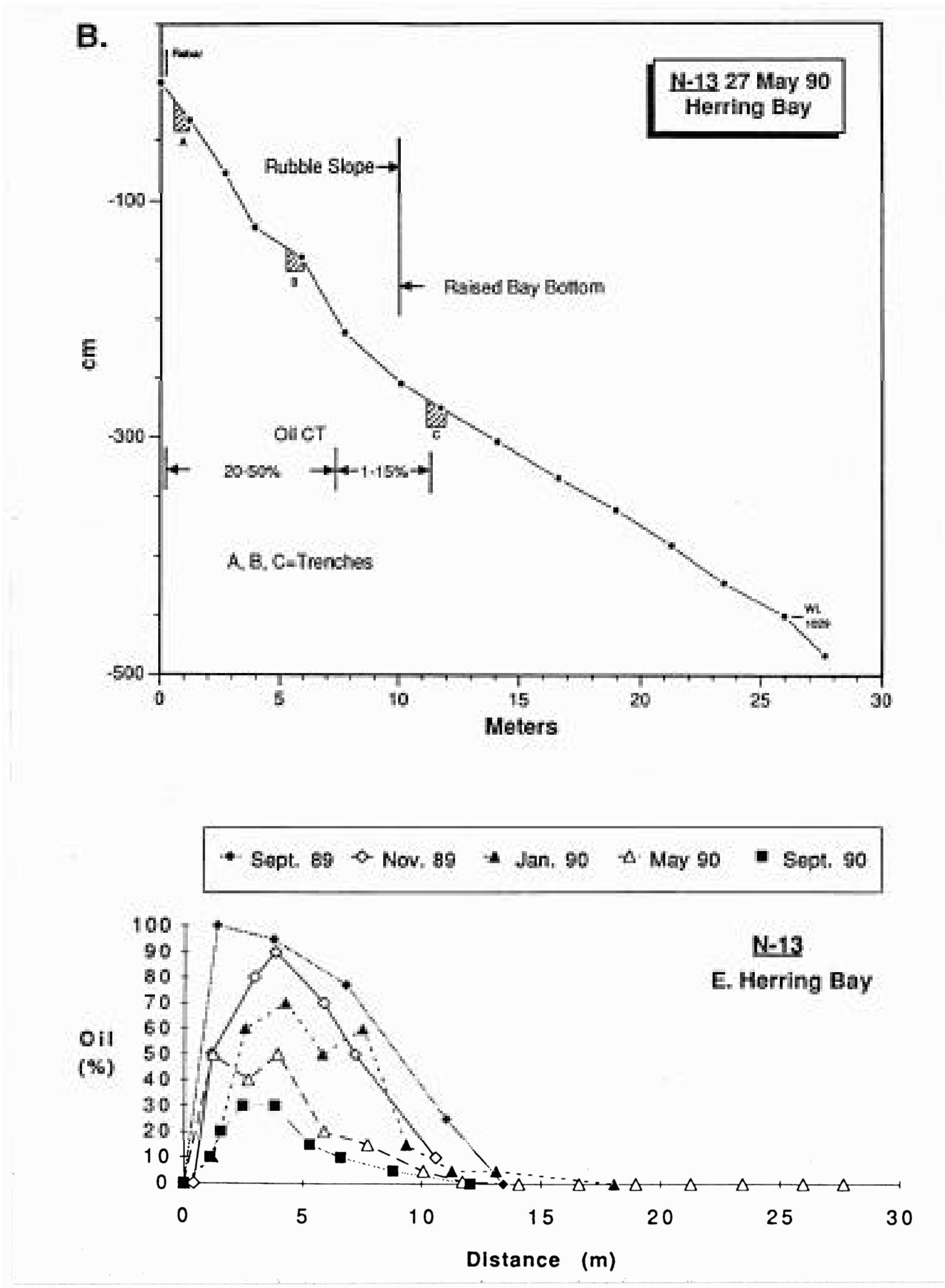


Figure 3-26. Continued. B) Topographic profile, illustrating the clear break between the rubble slope and the raised bay bottom. The distribution of oil coating (in percent) is also shown. C) Plot of the distribution of surface oil coverage between September 1989 and September 1990, based on visual estimates.

On sheltered *rubble slopes*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide line, forming a distinct oil band
- Penetrate into the crevices formed by the surface rubble and pool at the contact of the rubble and the surface
- Form pools and eventually pavements under heavy oiling
- Penetrate deeply into loosely packed rubble, causing long-term contamination of the subsurface sediments

Marshes

Depositional shorelines sheltered from wave action have a range of intertidal and supratidal environments, from barren saline flats (sabkhahs) to mangrove forests, depending mainly on the coastal climate. Some examples are given in Figure 3-27. This discussion is limited to marshes, which, as defined here, are restricted to wetlands containing emergent, herbaceous vegetation. Thus, they include salt, brackish, and freshwater marshes. But, the emphasis in this section is on marshes bordering water bodies such as estuaries, bays, lakes, and rivers, where floating oil slicks can impact the vegetation.

Marshes of the Southeastern USA

The estuaries on the coasts of South Carolina and Georgia are host to one of the most extensive developments of salt, brackish, and freshwater marsh systems in the USA. Many excellent, detailed studies of these marshes allow them to be used as a general model of marsh ecology and sedimentation. These marshes are well documented as being the primary food source for the coastal and nearshore ecosystem of the region. The importance of protecting these systems during oil spills, both in the southeastern USA and elsewhere, cannot be overemphasized.

Brackish and salt marshes originate as tidal flats that are sites of relatively quiet water deposition at the high-tide line. As the flat is built up to or slightly above man sea level, marsh grasses take root. Once grasses grow on the flat, the sedimentation process is accelerated because of the baffling effect of the plants.

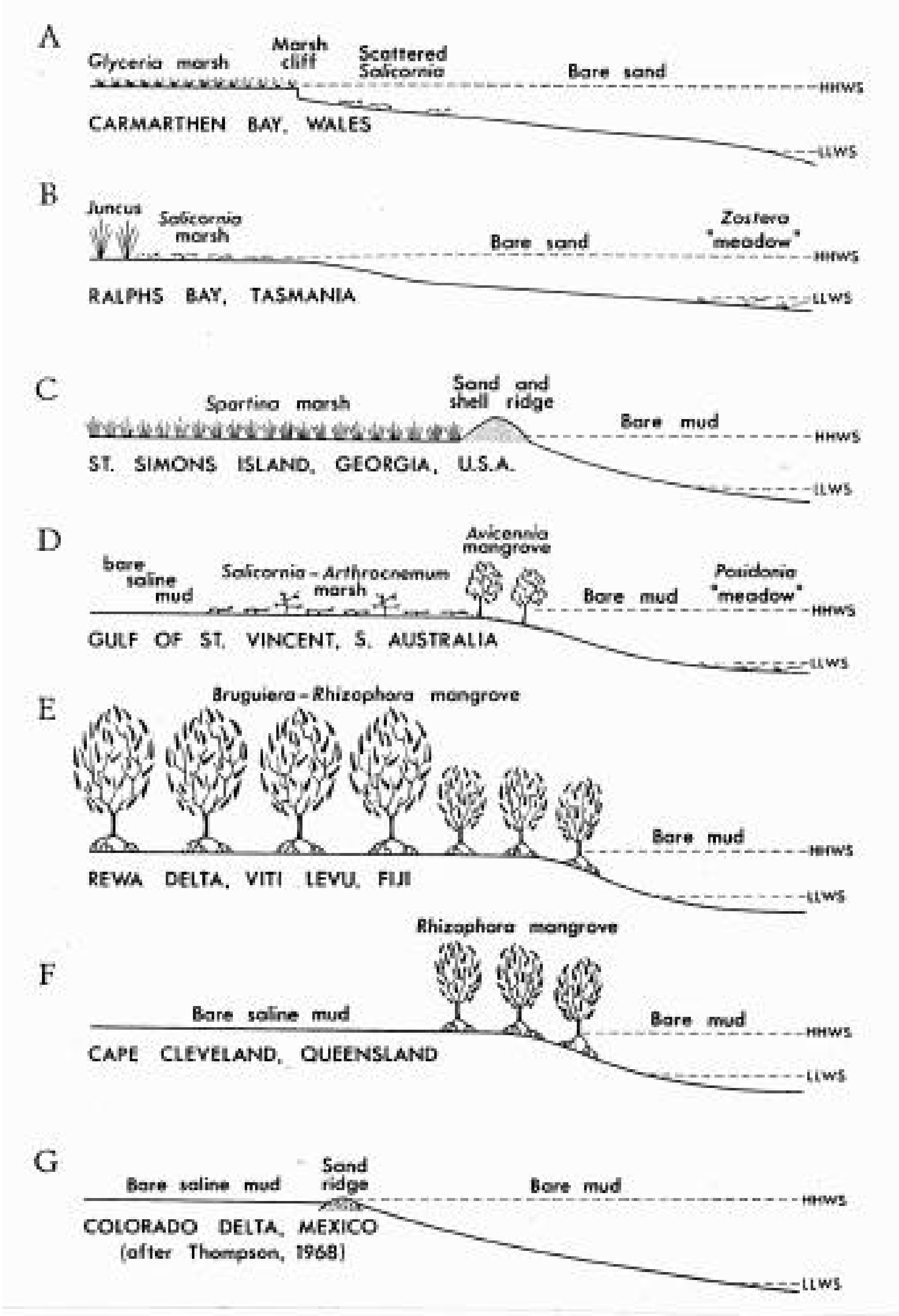


Figure 3-27. Relationship of coastal vegetation zones to geomorphic zones in a variety of climatic and physical settings. Profiles are diagrammatic and not to scale. (From Davies, 1973; Fig. 125.)

These marshes are, in effect, intertidal flats well-vegetated with halophytes (a plant that grows in salty soil; Basan and Frey, 1977). Marshes can prograde very rapidly, up to several cm/year, if the slope is flat and sediments are abundant.

For purposes of description, estuaries are usually subdivided into upper, middle, and lower zones. Freshwater marshes are most common in the upper estuary, where there are tides but very low salinities; brackish marshes occur in the middle estuary, where salinities generally average less than 15 parts per thousand (ppt); and salt marshes occur in the lower estuary, where salinities range from 15 ppt to the low 30s.

Lateral salinity changes up and down the estuary have a striking impact on the plant communities. Giant cordgrass (*Spartina cynosuroides*) is a conspicuous plant along the banks of the channels in both the upper and middle estuaries. Black needlerush (*Juncus roemerianus*) is by far the most common plant in the middle estuary, covering many thousands of acres in each estuary, and smooth cordgrass (*Spartina alterniflora*) dominates the lower estuary. See Figure 3-28 for a delineation of the distribution of the more conspicuous plants throughout estuaries of Georgia and South Carolina.

The lower reaches of the estuaries and landward margins of barrier islands of Georgia and South Carolina are bordered by salt marshes dominated by smooth cordgrass (*Spartina alterniflora*). The typical marsh profile found throughout the area is given in Figure 3-29. Most experts agree that plant distribution in the marshes is controlled by depth and duration of flooding (Barry, 1980); therefore, it is convenient to divide these marshes into a regularly flooded <u>low marsh</u>, the zone between mid-tide and neap high tide, and an irregularly flooded <u>high marsh</u>, which occurs roughly between neap and spring high tides.

Spartina alterniflora is the only plant that normally occurs in the low marsh zone, which is flooded 2-14 hours/day and has soil salt concentrations of 0.5-3.2 percent (Barry, 1980). The *Spartina* is usually quite tall (2-3 m at full growth) in the lower half of the profile (e.g., on creek banks and levees), but becomes dwarfed (10-50 cm) in the higher areas (e.g., between drainage creeks; behind levees). The reason for these differences in height is still a matter of conjecture.

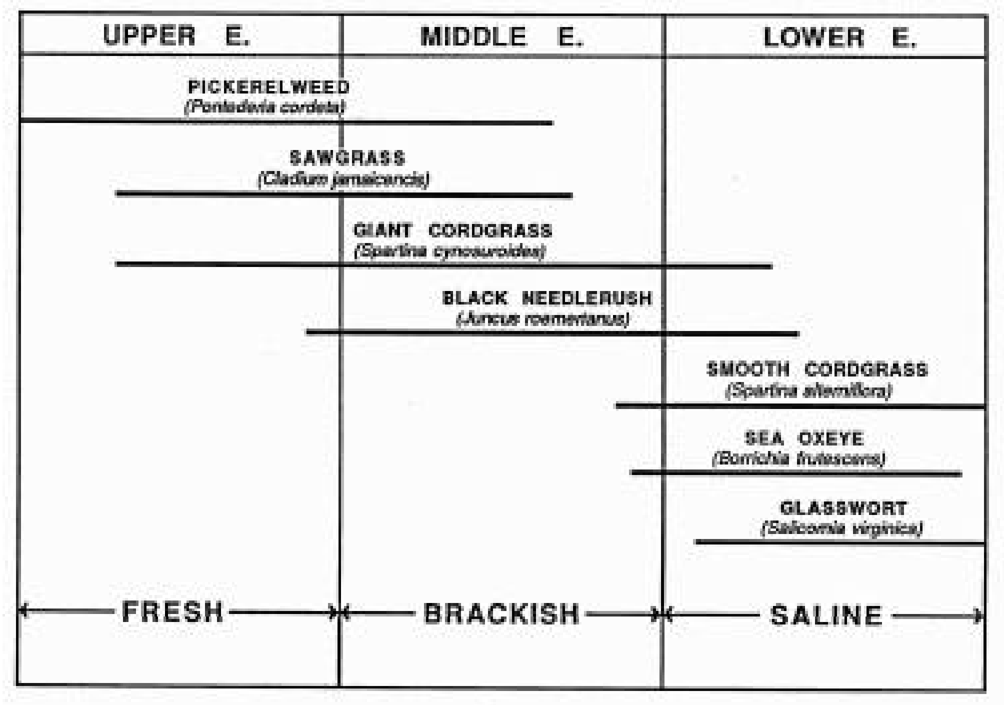


Figure 3-28. Occurrence of the most conspicuous plants in the marshes of the upper (fresh), middle (brackish), and lower (saline) parts of the estuaries of South Carolina and Georgia. (Modified after Stalter, 1974.)

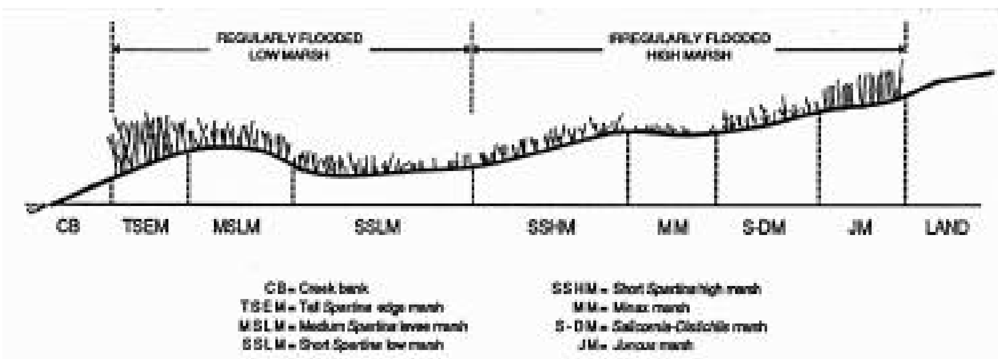


Figure 3-29. Typical profile of the salt marshes of South Carolina and Georgia. (Modified after Teal, 1958.) The "Minax marsh" zone is named after the dominant species of fiddler crab found there, *Uca minax*. The dominant plant is extremely short *Spartina alterniflora*.

At the lower elevations of the high marsh, zones of glasswort, or pickleweed (*Salicornia virginica*), sea oxeye (*Borichia frutescens*), and saltgrasses (*Distichlis spicata*) grow in soils with salt concentrations of 0.3-3.0 percent that are usually flooded daily. The upper high marsh, which is flooded mostly by spring tides, may be populated by *Juncus roemerianus*, in areas of lower salinity, and plants such as marshay cordgrass (*Spartina patens*), marsh elder (*Iva frutescens*), or sea myrtle (*Baccharis* sp.), in more saline areas.

Sediments in these marshes are typically muddy, and grain size decreases from the tidal channels to the highest portions of the marsh, except where runoff washes sand from adjacent sandy barrier islands or beach ridges onto the upper marsh (Edwards and Frey, 1977). Marsh sediments are always highly bioturbated, frequently being riddled with crab burrows (e.g., fiddler crabs; *Uca* sp.), having much the appearance of Swiss cheese.

The marsh sediments are commonly rich in organic matter, but they should not be referred to as “peat” unless the organic matter exceeds 70 percent of the sediment (by weight). Bona fide peat deposits rarely occur along tidal channels at the outer fringe of the marsh, where oil-spill impacts more often occur. Where peat does occur in estuarine marshes of the southeastern USA, it is usually found in the remotest, most freshwater portion of the marsh (e.g., in Snuggedy Swamp, South Carolina; Hayes and Sexton, 1989).

Marshes of California

In California, coastal wetlands are highly variable, depending upon the amount and frequency of freshwater influence. Southern California marshes are confined to narrow stream outlets with freshwater contribution only during the brief winter wet season (which can be completely missed during droughts). Thus, hypersaline conditions and salt-tolerant species dominate. Figure 3-30 shows a checklist of species within southern California salt marshes and Figure 3-31 shows the distribution of the most common halophytes by elevation. Soil salinity is the most important factor affecting salt marsh vegetation in Southern California (Zedler, 1982). Figure 3-32 shows a vegetation-succession model for Southern California marshes. The mature vegetation has *Spartina foliosa* restricted to the lower marsh, with the more salt-tolerant and opportunistic *Salicornia virginica* dominating the upper marsh.

HIGHER MARSH - LOWER MARSH

Wetland	Juncus acutus	Frankenia palmeri	Lasthenia glabrata	Cressa truxillensis	Atriplex watsonii	Salicornia subterminalis	Cordylanthus maritimus	Limonium californicum	Monanthochloe littoralis	Frankenia grandifolia	Triglochin concinnum	Suaeda californica	Distichlis spicata	Cuscuta salina	Jaumea carnosa	Batis maritima	Salicornia bigelovii	Salicornia virginica	Spartina foliosa
Tijuana Estuary	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Sweetwater Marsh	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Mission Bay Marsh						●		●	●	●	●	●	●	●	●	●	●	●	●
Penasquitos Lagoon	●		●	●		●	●	●	●	●		●	●	●	●			●	
San Dieguito Lagoon	●		●	●		●		●	●	●		●	●		●			●	
San Elijo Lagoon				●		●				●			●		●			●	
Batiquitos Lagoon	●		●	●		●		●	●	●			●		●			●	
Agua Hedionda Lagoon	●			●		●			●	●		●	●	●	●			●	
San Luis Rey River Marsh	●									●			●		●			●	
Santa Margarita River Marsh	●		●	●	●	●		●		●		●	●	●	●			●	
Las Flores Marsh						●				●			●		●			●	
San Mateo Marsh										●			●	●	●				
Upper Newport Bay Marsh	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bolsa Chica Marsh	●				●	●		●	●	●		●	●		●	●	●	●	●
Anaheim Bay Marsh	●			●	●	●		●	●	●	●	●	●	●	●	●	●	●	●
Ballona Wetland				●		●				●		●	●		●			●	
Malibu Creek																			
Mugu Lagoon	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
McGrath Lake	●									●			●		●			●	
Santa Clara River	●									●			●					●	
Carpinteria Marsh			●	●	●	●	●	●	●	●	●	●	●	●	●			●	
Goleta Slough			●	●	●	●		●	●	●	●	●	●	●	●			●	
Deveraux Lagoon				●						●			●	●	●			●	

Figure 3-30. Check list of species within salt marshes of southern California wetlands. Data are cumulative lists from a variety of sources, including observations of W. Ferrens (UCSB Herbarium) and J. Zedler. Wetlands with a history of good tidal flushing are boxed on the right-hand column. (From Zedler, 1982.)

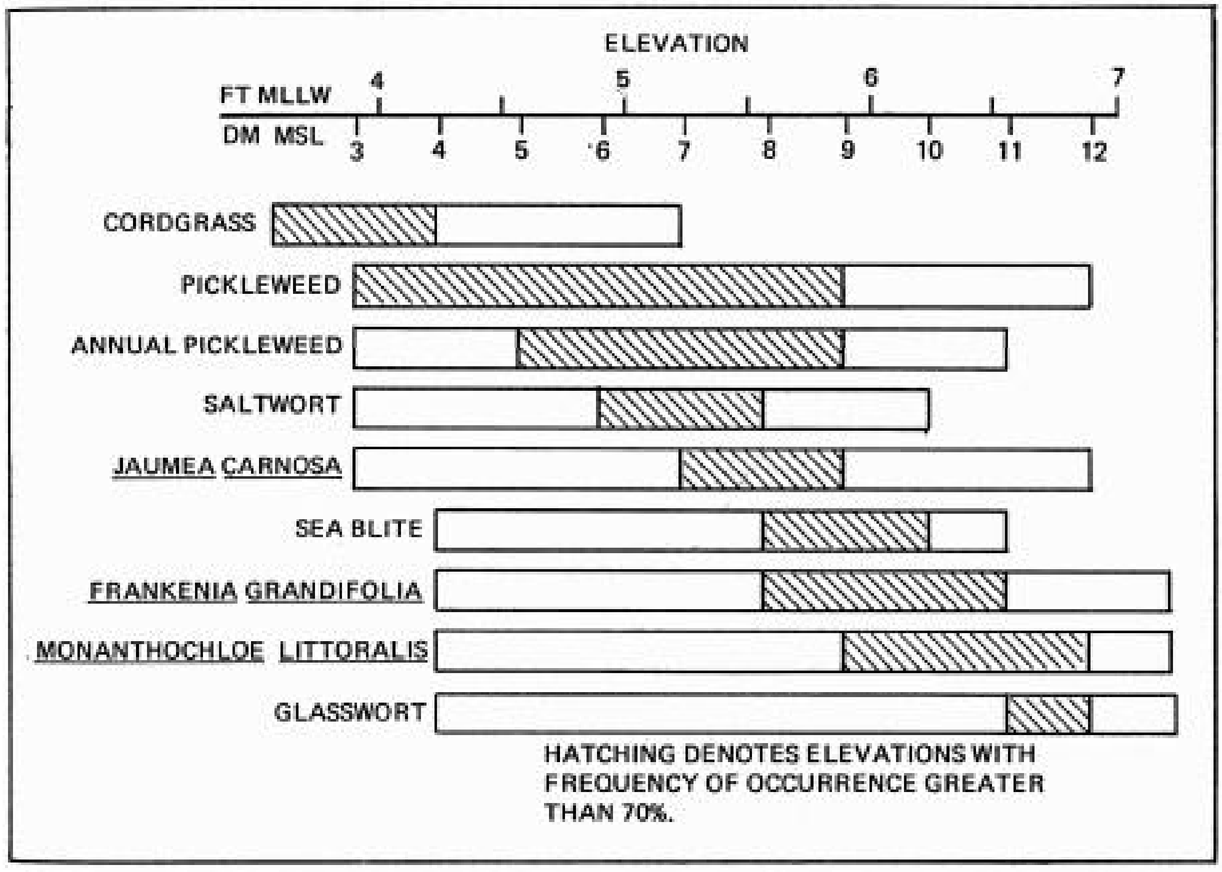


Figure 3-31. Distribution of the most common halophytes by elevation, at Tijuana Estuary. Data from Anaheim Bay were used to extend the ranges of species beyond the 3- to 12-dm MSL range observed at Tijuana Estuary. (From Zedler, 1982.)

USUAL CONDITIONS = HYPERSALINE SOILS

Habitat becomes available for colonization.

Opportunistic species invade by seed (Salicornia virginica, S. bigelovii, Suaeda californica).

Salicornia virginica achieves early dominance due to
- --high growth rates under saline conditions
- --vegetative spread
- --perennial growth

FLOODS OR HEAVY RAINFALL EVENTUALLY OCCUR

Germination of halophytes is stimulated.

Spartina foliosa may establish patches if a nearby source is available.

Spartina foliosa may spread vegetatively, especially at lower elevations.

LONG PERIODS OF HYPERSALINITY FOLLOW, INTERRUPTED BY OCCASIONAL WET YEARS

Species distributions continue to shift in response to environmental changes; Salicornia retains competitive advantage under more saline conditions.

Spartina foliosa expands substantially during years of less saline conditions and at lower elevations.

A mixture of species results, with Spartina foliosa restricted to the lower marsh.

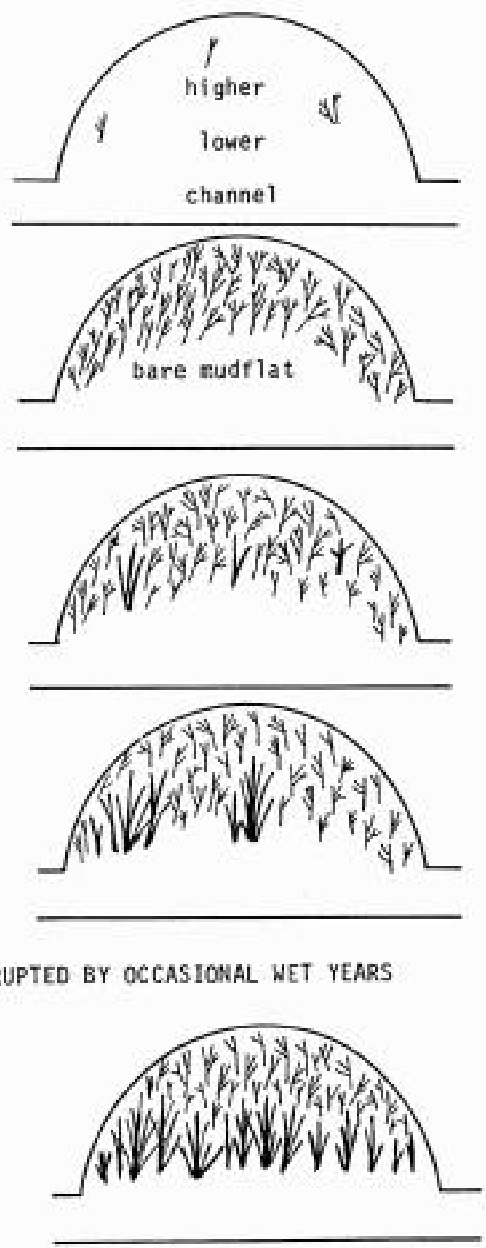


Figure 3-32. Conceptual model of species establishment and spread in southern California salt marshes. (From Zedler, 1982.)

San Francisco Bay and the Sacramento-San Joaquin River Delta have a diverse and variable salt marsh community, with about 125 species of vascular plants reported in the area. The following summary of the distribution of species is from Atwater et al. (1979).

Common pickleweed (*Salicornia pacifica*) and California cordgrass dominate the tidal-marsh vegetation of the Bay, with common pickleweed monopolizing the vegetation at elevations near and about MHHW. Other common plants include salt grass (*Distichlis spicata*), marsh Grindelia (*Grindelia humilis*), halberd-leaved saltbush (*Atriplex patula*), alkali heath (*Frankenia grandifolia*), and fleshy Jaumea (*Jaumea carnosa*). California cordgrass fringes tidal-marsh plains where they descend into mudflats; near MTL it forms pure stands. Common tule (*Scirpus acutus*), Olney's bulrush (*Scirpus olneyi*), common reed (*Phragmites communis*), and cat-tails (*Typha* sp.) dominate islands of pristine marsh in the Delta. The tidal marshes of San Pablo Bay, Carquinez Strait, and Suisun Bay represent complex transition communities, which are even more complex because of long-term changes in salinity from water diversions and multi-year droughts. There can be gradual changes in soil salinities during droughts which favor or discourage certain species.

Behavior of Oil in Marshes

Most of our experience comes from the study of spills affecting vegetation under tidal influence in coastal estuaries. And most of the studies have been of marshes dominated by *Spartina*, sp. Based on the available data, there are significant differences among species assemblages.

When oil comes in contact with a marsh in a tidal setting, it generally behaves in the following manner:

- Oil adheres readily to the vegetation; in fact, marsh vegetation is a very effective oil sorbent.
- The band of coating will vary widely, depending upon the tidal stage at the time that the oil slicks are in the vegetation. There can be multiple bands.
- Large slicks will persist through multiple tidal cycles and coat the entire stem from the high-tide line to the base.

- Fresh crudes and heavy oils will tend to “slide” down the stem over time in warmer weather and pool on the sediments at the base of the plant.
- Weathered oils do not “slide” as much; the oil stays on the vegetation.
- If the vegetation is thick, heavy oil contamination can be restricted to the outer fringe, with penetration and lighter oiling up to a 10 m width.
- Lighter oils (light refined, fresh crudes) can penetrate deeply, to the limit of tidal influence.
- Medium to heavy oils do not readily adhere to or penetrate the wet, muddy sediments, but they can pool on the surface and in burrows.
- Light oils can penetrate the top few cm of sediment and deeply into burrows and cracks (up to 100 cm).

Factors Affecting the Impacts of Oil on Marshes

Although every spill is a unique combination of events, there are several factors which affect the behavior and impact of the oil on the marsh ecosystem:

1) Oil type
2) Extent of contamination of the vegetation
3) Degree of contamination of the sediments
4) Exposure to currents and waves which effects the speed of natural removal
5) Time of year of the spill
6) Species sensitivity
7) Damages associated with cleanup activities

Impacts by Oil Type

It has been shown that light refined products have the greatest acute toxicity to marsh vegetation, when compared to other types of oil.

Spill/Experiment	**Observations**
Florida barge, No. 2 fuel oil (Burns and Teal, 1979)	*Spartina* killed; no regrowth after 16 mo. where sediments had > 2,000 ppm fuel oil

Bouchard No. 65 barge, No. 2 fuel oil, Buzzards Bay, MA (Hampson and Moul, 1978)	Total mortality of *Spartina* and *Salicornia*; no reseeding or rhiozome growth in 3 yrs in zone heavily oiled; 2-4x slower growth elsewhere. Erosion rates were 24x greater in oiled areas.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	All oils caused mortality within 3 weeks; after 5 mo., only plots with No. 2 fuel oil had reduced growth of plants, compared with 2 crudes and No. 6 fuel oil.

In contrast, observations of spills of crude oils and heavy refined products show mostly short-term impacts, and recovery within 1-3 years (Baker, 1971; Baca et al., 1985; 1977; Bender et al., 1980; Michel, 1989). There are even studies which show that an increase in standing crop of the marsh grass occurs following some spills (Hershner and Moore, 1977). Crude oils contain nitrogen, and when nitrogen is limiting, there can be growth simulation under some conditions (Leendertse and Scholten, 1987). However, the net impact is always negative.

Extent of Vegetation Contamination

The extent of vegetation contamination is another very important factor. Many plants can survive partial oiling; few survive when all or most of the stem is coated. Examples from the literature are:

Spill/Experiment	**Observations**
Cape Fear River, NC, No 6 fuel oil (Baca et al., 1983)	After 5 mos., lightly oiled *Spartina* had recovered; heavily oiled areas showed reduced no. of plants/m^2 and sediment oiling.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	Highest mortality was observed in plots where oil was applied to entire plant surface, compared to on the sediment and lower plant
Field oiling with crude oil on *Spartina* stems, not leaves (DeLaune et al., 1979)	No initial mortality or difference in above-ground biomass or stem density for 2 growing periods.

Degree of Sediment Contamination

The degree of contamination of sediments is another very important factor, which can prolong impacts to marsh ecosystems for many years, compared with the initial loss of oiled vegetation. Slower recolonization rates are frequently related to hydrocarbon levels in the sediments, though it should be noted that the composition of the oil is as important as the total petroleum content. That is, fresher oil and refined products have higher percentages of the more toxic fractions in oil, whereas heavy oils have lower initial and long-term toxicities. Examples are:

- 5,000-50,000 ppm of a light crude slowed growth of *Spartina* for 18 months in field oiling experiments. Growth was unaffected at lower concentrations (Alexander and Webb, 1987).
- No regrowth of *Spartina* in sediment with >2,000 ppm No. 2 fuel oil following the *Florida* spill (Burns and Teal, 1979).
- In 2-year studies of restoration through sediment stripping following a No. 6 fuel oil spill in the Potomac River, Krebs and Tanner (1981) found:
  -Little impacts to vegetation at concentrations <2,000 ppm
  -Rhizome death and no regrowth at concentrations >10,000 ppm.

Exposure

The physical setting of the oiled marsh, relative to exposure to waves and currents, is one of the most important factors controlling the persistence of oiled vegetation and overall rate of recovery. Exposure can work to speed recovery, but, in some cases, it can also work to increase erosion after plant roots die and before new growth can occur.

Oil deposited along the outer fringe is removed as the vegetation dies back and is exported. There are many examples of oiled vegetation along tidal rivers where, after one season, there is no visual evidence of oiled vegetation or sediments. Boat wakes, river currents, and tidal flushing are important natural removal processes, and they are usually much more effective than any man-made cleanup. In contrast, oil spilled in interior settings, such as from pipelines crossing wide marsh or swamp areas, have no physical removal mechanisms, and the oil can only weather in place or be removed by cleanup efforts.

Seasonal Effects

The timing of an oil spill, relative to the plant's growing season, can affect the nature and duration of the spill impact. In general, oiling during the dormant winter season has the lowest impact, whereas oiling of vegetation during the summer growing season had longer effects. The mechanisms responsible for the slower recoveries from a spill during the growing season have not been adequately studied, but probably are related to plant stress at a time when the plant's resources are being fully expended. For example, oiled plants rarely flower and oiled flowers do not produce seed (Baker, 1979), resulting in loss of the year's seed production. Alexander and Webb (1985) found that, in experimental plots, the time of year the oil was applied did not influence the response of *Spartina* to oil when it was applied to sediments and the lower portions of the plants; however, when the entire plant surface was oiled, impacts were greater for a May versus a November oiling.

If oil persists, then there can be delayed impacts to marshes. Thomas (1977) reported delayed toxicity of heavy surface oiling by No 6 fuel oil to *Spartina* the second year after the *Arrow* spill in Chedabucto Bay.

Species Sensitivities

There are some known variations in sensitivity among species, however, very little else is known about other species. In general:

- Annuals are less resistant than perennials, which have large roots systems that allow them to regrow after damage to aerial portions (Getter et al., 1984); for example, the annual *Salicornia* is less resistant than other species, such as *Spartina*, to oil spills (Baker, 1971)
- *Juncus* is more resistant than *Spartina* to chronic spills (Lytle and Lytle, 1987)

Impact of cleanup

Sometimes, the greatest impact of an oil spill on a marsh is a result of the cleanup efforts. The greatest damages derive from:

- Destruction of the root system by trampling
- Mixing oil deeper into the sediments, slowing weathering and removal
- Removal of surface sediments suitable for supporting new growth
- Smothering of vegetation by mobilized sediments
- Exposure of the interior of the plant to toxic substances in the oil

Nowadays, responders are very sensitive to causing more harm during cleanup than what will result from the oil alone. Most of the time, very little cleanup is conducted in marshes, other than passive collection of oil onto sorbents. However, there are two conditions where cleanup can be warranted: 1) when heavy oil has pooled in a marsh sheltered from natural removal processes, and 2) when other uses or resources present are at risk from leaving the oil in place. The biggest controversy is over cutting of the oiled vegetation. Again, most all of the experience is vegetation cutting is of *Spartina* along the east and Gulf coasts. The literature is summarized below.

Spill/Experiment	Observations
Cape Fear River, NC, No 6 fuel oil (Baca et al., 1985)	After 15 mos., uncut *Spartina, Scirpus, and Phragmites* showed good recovery; cut *Spartina* showed no recovery.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	Clipped plots showed regeneration by growth of new stems and seedlings, but No. 2 fuel oil and Light Arabian crude inhibited stem emergence.
Crude oil spill, TX into sheltered *Spartina* marsh (Holt at al., 1978)	6 mos. later, only heavily oiled vegetation showed impacts; clipped areas showed slightly better recovery than non-cleaned, except where physical damage to roots occurred.
Nepco 140 barge, No. 6 fuel oil in St. Lawrence River (Alexander et al., 1981)	Cattails were cut below water level in June 1976. Next spring growth was normal but no flowering occurred.
Light Arabian crude in Neches River, TX in January 1979 (McCauley and Harrel, 1981)	Cut *S. patens* showed no or minimal growth, whereas leave-alone plots showed normal growth through next growing season.
Louisiana crude applied to sediment surface of plots (DeLaune at al., 1984)	Cutting of vegetation reduced plant growth and slowed rate of recovery, compared with oiled only and unoiled plots.

Mangroves and Coral Reef Communities

The dominant estuarine and nearshore coastal communities in tropical and some subtropical regions are mangroves and corals. These environments are very important to the ecological balance of many of the marine ecosystems in the tropics. Like the salt marshes of the temperate zones, mangroves and coral serve as nursery habitats and have a high diversity and density of animal and plant species. Mangrove photosynthetic activity provides the base for secondary productivity, in the form of leaf detritus, that supports important commercial and recreational fisheries. They provide habitat for endemic and endangered species.

The impacts to these environments from spilled oil is dependent on the amount and type of oil spilled, extent of weathering of the oil prior to landfall, and the physical characteristics of the impacted area (water depth, exposure to waves, nearshore and intertidal topography, sediments, etc.). Each of these factors will be discussed as they determine the sensitivity of coral and mangrove ecosystems to oil spills.

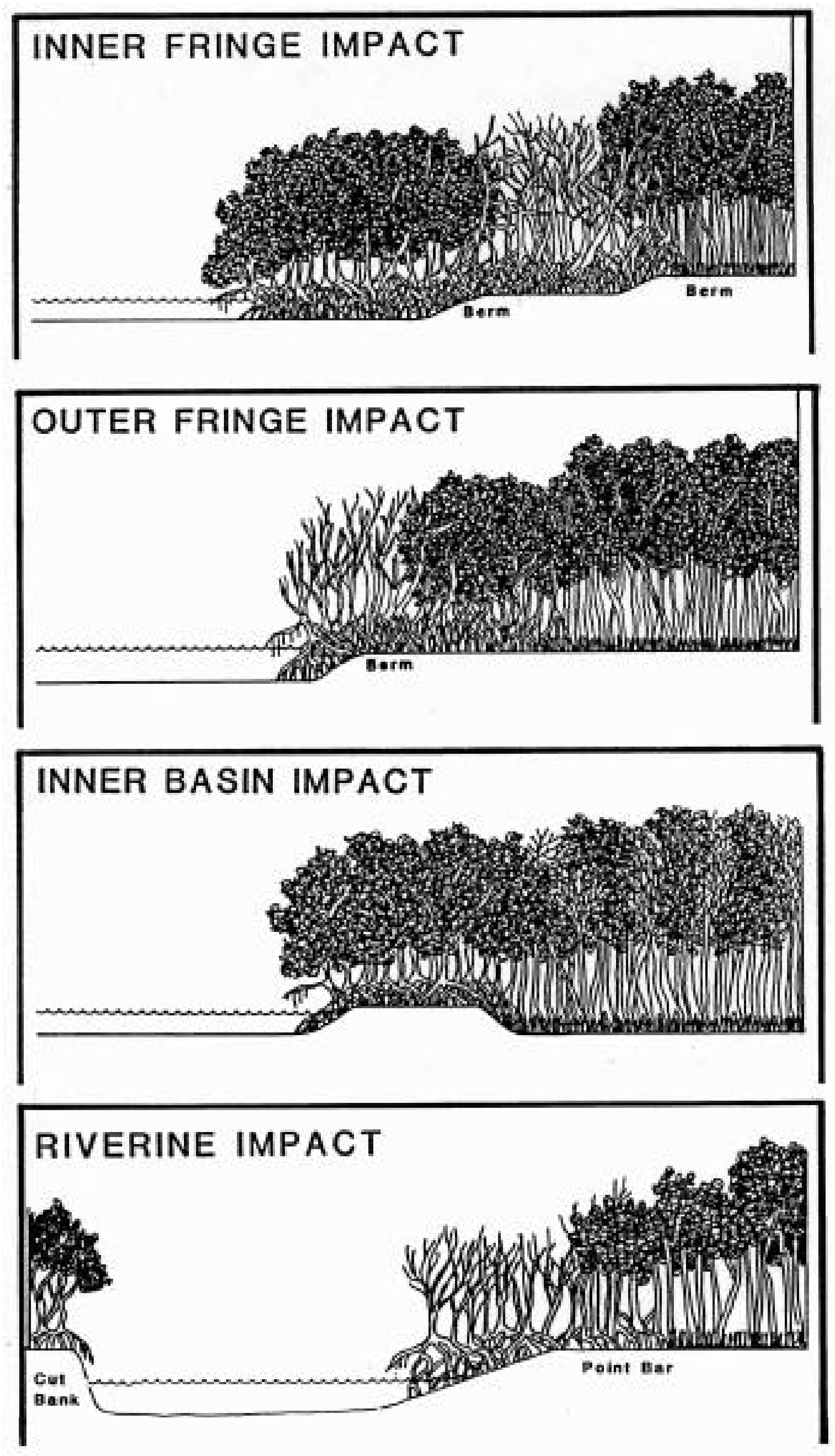
Mangroves

The two most common species of mangroves found in the United States are the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*). The red mangroves have gracefully curving prop roots which extend a meter or more above ground and are covered with small pores, called lenticels, through which oxygen diffuses when exposed to the air at low tide. Because mangroves grow in anaerobic soils, they obtain most of the oxygen needed from the atmosphere. Black mangroves uptake oxygen through small roots, called pnematophores, which extend 20-30 centimeters straight up above the soil from an underground root system. Where both species exist, red mangroves occur in the low- to mid-intertidal zones, whereas black mangroves are more common in the upper intertidal and supratidal zones. Black mangroves are less tolerant of high salinities, so they grow better where there is less exposure to salt water inundation and some fresh groundwater influence. The white or buttonwood mangrove (*Laguncularia racemosa*) occurs primarily seaward of the black mangrove.

Where mangrove forests occur, water depths are very shallow and most of the forest is exposed during low tide on a regular basis. They are frequently fronted by shallow seagrass or reef flats. Topographic elevations in the forest control the location and extent of oiling from floating slicks. Figure 3-33 depicts four types of physical impacts likely to occur during oil spills (Getter et al., 1981).

<u>Inner fringe impacts</u> occur when there is a berm behind mangroves growing in the subtidal or low intertidal areas. The oil passes through the open network of prop roots and collects at the front of the berm, causing defoliation and mortality of both seedling and adult trees at the inner stand of mangroves. The prop roots of the outer mangroves are oiled, but only as a thin band. Greatest impacts occur where the oil is concentrated in the sediments and wrack is piled on top of the berm. This

Figure 3-33. Four models of the distribution of oil spill effects in mangroves.



interior berm is either inherited topography or built by the accumulation of sediment and debris carried into the forest by storm waves. The berm serves to prevent the transport of oil deeper into the forest, so where present, the berms are the *de facto* interior limit of oil penetration. The natural rate of flushing of oil from these inner berms is highly variable. Large amounts of debris may be indicative of accumulation zones with slow removal rates. Heavy debris also acts as a natural sorbent for oil, with the potential as a long-term leaching source.

Outer fringe impacts are likely along relatively steep intertidal zones where red mangroves commonly occur in a narrow band. Because of the narrow intertidal zone, there can be heavy oiling of the sediments and any accumulated debris. The steepness of the intertidal zone may be due to a wave-built sand beach or a steep rocky shore. The presence of a sand beach indicates exposure to waves and the potential for removal of stranded oil by natural processes. A rocky substrate may indicate wave exposure, but is not as diagnostic as a depositional beach. There may be very sheltered bays where mangroves have been established on a rocky substrate. However, oil is less likely to contaminate and persist in the rocky substrate than in fine-grained sediments.

Inner basin impacts occur where there is a low overwash berm in front of a shallow depression or interior basin. Oil gets washed over the low berm and is trapped in the basin. Although the oil can spread over a large area, the oil is less likely to be concentrated in a narrow band, thus partial defoliation as shown on Figure 3-33 often occurs. Persistence of the oil can be long term, depending on the degree of natural flushing in the basin. In more exposed areas, oil can be removed from the system within several months, particularly for refined products and light crudes. Heavy oils are always more persistent because of their higher viscosities. In sheltered areas, oil persistence of years is likely.

Riverine impact is very similar to outer fringe impact, however, it occurs only on river point bars, and it can be more extensive than outer fringe impacts. Of course, if the spill occurs during unusually high water levels, the oil can be carried over the bars and river levees, into the interior basin forests. Riverine environments are, however, relatively high energy, being exposed to both riverine and tidal currents which are effective in natural removal of the oil.

The type of oil greatly affects the nature and degree of impacts to mangrove ecosystems. Refined petroleum hydrocarbons with large amounts of the water-soluble aromatic compounds (e.g., jet fuels, gasoline) are more acutely toxic to mangroves at lower concentrations than are crude oils and heavy refined products.

The best example of the high acute toxicity of light refined products is the 1986 spill of 60,000 gallons of JP-5 from the Roosevelt Roads Naval Station in Puerto Rico (RPI, 1987). The oil had a low viscosity so there was no smothering and the only impacts were due to direct exposure and poisoning via absorption through the pneumatophores and prop roots. An estimated 70 percent of the oil evaporated within 24 hours, however, a thin slick was blown across a small bay and was quickly deposited in a tidal mixed species assemblage of red, black, and white mangroves, with reds dominating the seaward zone and blacks dominating the landward zone. Trees exhibited stress in 10 days, and within 5 months, 5.5 hectares of trees were dead. This acreage of mortality is disproportionately large for the number of gallons spilled, compared to heavier oils.

It was interesting to note that seedlings survived more than adult trees because the seedling roots were buried in sediments and avoided acute exposure. Seedling mortality for the period 6-9 months post-spill averaged 30 percent, which not different from non-oiled sites. Chemical analysis showed no residual oil in the sediments, so natural recovery was predicted to occur unimpeded by contaminated sediments. Natural recovery depends on adequate supply of seeds and growing conditions, including regular flushing by clean seawater, which provides stabilized surface and interstitial water salinities, brings in nutrients, and increases colonization rates by transport of seeds into the area. Following this incident, a restoration plan was developed to open selected channels to increase the level of circulation in parts of the forest which had low flushing rates.

Heavier oils (Bunker C and medium to heavy crudes) lead to chronic exposure and chronic impacts to the mangrove ecosystem. Oil impacts to the trees are related to the physical coating of the roots, which prevent gas exchange, and from chronic exposure to oil-contaminated sediments. Such exposure can result in slow defoliation and death over a period of time. If mortality does not occur, signs of severe stress will be manifested, such as partial defoliation, low survival of propagules, leaf deformities, reduced leaf size, and increased insect infestation (Lewis, 1983).

Seedling and propagules die when they are coated with oil, even when the oil has weathered for a few days before stranding. It should be noted that where defoliation and death of adult trees occurs following a spill, seedling density increases significantly. Because of the newly opened canopy, more light reaches the seedlings and they have higher sprouting rates. However, where the sediments remain contaminated, long-term seedling survival is lower. Even eight years after the *Zoe Colocotronis* oil spill in Puerto Rico, seedlings in heavily oiled sediment appeared chlorotic, stunted, and insect damaged (Cintron et al., 1981). After the 1986 Texaco spill of 50,000 barrels of a medium-light crude oil in Panama, sediments were toxic to planted seedlings for the first six months post-spill, but after twelve months survival was the same for control and oiled sites (Teas et al., 1989).

Impacts to the associated fauna and flora can be severe. Red mangrove prop roots support a dense community of attached algae, mussels, oysters, and barnacles, which are frequently directly killed under moderate to heavy oil coating. Crabs are particularly hard hit, whereas gastropods appear to be able to shift to less contaminated areas, if present (Getter et al., 1980; Jernalov et al., 1976).

Laboratory studies have shown wide variability in the relative toxicity of different types of oil in sediments on seedling survival. Table 3-2 summarizes the results of experiments by Getter et al. (1984). No. 2 fuel oil was shown to be the most toxic, compared to Bunker C and two crude oils. Bunker C was the least toxic oil tested. Black mangroves exhibited higher mortalities and sublethal stress effects than red mangroves at the same dosages and were found to be especially sensitive to aromatic compounds. Similar results were reported from studies conducted at the Universiti Sains Malaysia (Lai and Feng, 1984).

Extensive laboratory and field studies were conducted in the 1980s to determine the relative toxicity of oil versus dispersed oil. In fact, the previously mentioned laboratory studies were the oil-only controls for comparison with dispersed-oil treatments. These studies have been conducted by RPI (Getter et al., 1984; Ballou et al., 1985) and researchers at Universiti Sains Malaysia (Lai and Feng, 1984). The results of these studies include:

Table 3-2. Concentrations of different types of petroleum hydrocarbons and observed toxic effects from laboratory experiments (Getter et al., 1984).

CONCENTRATION	FUEL TYPE (in ppm)	TOXIC EFFECTS
100	Diesel	Growth alteration
300	No. 2	92% mortality; survivors with no new leaves
300	Bunker C	24% mortality; survivors with fewer new leaves
300	South Louisiana crude	20% mortality; survivors with fewer new leaves
300	Kuwait crude	No mortalities; increased number of new leaves
1,000	Diesel	Growth deformities
10,000	Diesel	Lethal
38,600	Bunker C No. 2 Kuwait crude	Fewer new leaves; depressed weight gain
100,000	Diesel	Lethal

- Dispersed Bunker C was less toxic than undispersed Bunker C.
- Dispersed light Arabian crude and No. 2 fuel oil resulted in increased defoliation.
- Toxicity can result from oil entering roots and being drawn up the stems and leaves by transpiration.
- In field experiments, dispersed oil had minor effects on mangroves whereas untreated oil caused extensive defoliation and death to adult trees, lower survival rates of planted propagules, and long-term sediment contamination.
- Black mangroves are more sensitive to oils, both dispersed and untreated.

Based on both laboratory and field studies of oil spills in mangroves, the following comments and recommendations are made:

<u>Light Oils (Gasoline, Jet Fuel, No. 2 Fuel Oil)</u>

- Fresh spills will have acute, toxic impacts to both trees and intertidal biota.
- Sunny, windy weather will speed evaporation which will lessen water-column and intertidal impacts.
- These light products will penetrate deeply into the forests, stopping only at the high-tide line. Highest concentrations will occur at the high-tide line and in detrital material.
- Persistence of oil in sediments should not be great, unless there has been physical mixing into the substrate by wave or cleanup efforts.
- No. 2 fuel oil will have the greatest persistence; it can persist and remain toxic for many years if it penetrates burrows and prop root cavities.
- It is generally impossible to physically protect a fringing mangrove forest.
- Deployment of booms is seldom effective because of low viscosity of these light products and importance of water-column transport mechanisms, but it should be attempted, particularly at stream mouth.

<u>Crude Oil/Heavy Refined Products</u>

- Oil will coat intertidal zone, with heaviest concentrations either at the outer fringe or the high-tide line.
- Penetration into the forest will be limited by the amount of oil, forest density, and oil viscosity; weathered, emulsified oils penetrate less.
- Oil can pool onto sediment surfaces and accumulate heavily in detrital material such as seagrass wrack.
- Toxicity is due to coating and sediment contamination; there is little difference in toxicity among the heavier crude oils and refined products.
- Because of low physical energy in mangrove swamps, oil persistence is great and sheens are generated for months.
- Booms should be deployed to attempt to protect the most sheltered areas where greatest persistence is likely.

Cleanup Recommendations

- Under light accumulations of any type of oil, no cleanup is recommended.
- If sheens are present, use sorbent booms to pick up the oil as it is naturally removed, being sure to change booms frequently.
- The only light refined product that might require cleanup is No. 2 fuel oil/diesel because of the potential for sediment contamination.
- Heavy accumulations could be skimmed or flushed with low-pressure water flooding, as long as there is NO disturbance or mixing of oil into the substrate. If substrate mixing is likely or unavoidable, it is better to leave the oil to weather naturally.
- Under moderate to heavy accumulations of crude or heavy refined products, a detailed, site-specific cleanup plan will be required. This cleanup plan should be prepared by experienced personnel and include:
    1. General map of entire area impacted and locations of specific areas to be cleaned.
    2. Detailed maps of each specific area showing the oil locations and type of cleanup to be performed at each location.
    3. Definition of each type of cleanup.
    4. Specific restrictions to prevent further damage.
- Oily debris should be removed, taking care not to disturb the substrate.
- The vegetation should never be cut or otherwise removed.
- Sorbents can be used to wipe heavy oil coating from prop roots in areas of firm substrate and with close supervision.

Coral Reefs

Coral reefs are mostly subtidal in nature, although the most shallow portions of some reefs can be exposed during very low tides. The three major categories of reefs are:

- Fringing reefs - long, narrow bands of coral reefs parallel to and near the shoreline. When near coastal development, they are susceptible to stress from sedimentation and chronic pollution.

- Barrier reefs - similar to fringing reefs except thay are further offshore and much broader (e.g., the Great Barrier Reef of Australia).
- Atoll reefs - reefs formed by buildup of coral on the rim of a subsiding volcano. They are circular or portions of a circle, forming a sheltered lagoon.

All of the reefs are completely submerged during high tide, and only a few reefs are routinely exposed during normal low tides. More commonly, reefs are exposed only during extreme low tides a few times a year.

Review of the literature shows that there have been relatively few studies of reefs following exposure to oil spills. There are several very good summaries of the literature as of the early 1980s. Loya and Rinkevich (1980) and Ray (1980) compiled data on known oil spills near coral reefs and their effects on coral reef communities. Tetra Tech (1982) prepared a draft report for the American Petroleum Institute on ecological impacts of oil spill cleanup on nine different habitats, including coral reefs. They updated the Loya and Rinkevich (1980) list of oil spill case histories, for a total of fifteen. These case histories have very little quantitative data, but they mostly indicate no or very short-term impacts to coral reefs, except where chronic spills occured. It is important to note that these case histories looked for acute impacts, whereas it is more likely that any negative effects will be manifested as sublethal responses (Fucik et al.,1984).

There have been very few additional studies of coral reef impacts by oil spills reported in the literature since the mid-1980s. There have been laboratory studies, comparing oil versus dispersed oil impacts (Dodge et al., 1984; Knap et al., 1985; Wyers et al., 1986; Knap, 1987), and studies on the effects of chronic oil pollution (Bak, 1987). The only exception is the extensive followup to the 1986 Texaco spill in Panama which impacted shallow coral reefs near the Galeta Marine Laboratory of the Smithsonian Tropical Research Institute. Guzmán et al. (1991) reported on the short-term impacts of the spill after 2.5 years, with delayed and extensive patterns of injury observed. This spill had three factors which contributed to the extent and degree of damage to coral reefs: 1) large amounts of fresh oil, 2) shallow-water reefs, and 3) chronic exposure for months as the oil leached out of adjacent mangroves.

The potential for impacts from oil spills on reefs can be divided into three main categories, as summarized below:

Low risk

- Reefs located at greater than five meters water depth at low tide; dilution should reduce oil concentrations in the water column to below acute toxicity levels.

- High energy setting could mix fresh oil into the water column, but exposure is more likely to be short (hours to one day).

- Studies have shown healthy reefs rapidly recover from sublethal effects [i.e., normal carbon fixation restored within 5-24 hours after exposure (Knap, 1987)].

- Where the reef is exposed to heavy surf, deposition of oil is unlikely.

Medium risk

- Reefs located in water depths of 1-5 meters below low water, where high concentrations of dissolved and particulate oil are possible, especially when the oil slick is fresh.

- When the oil is fresh, toxic concentrations may cause acute impacts; more likely sublethal impacts may occur (NAS, 1985):

  -Increased algal growth

  -Slower growth rates

  -Lower fecundity (lower number of ovaria per polyp, fewer larvae per coral head, and lower settlement rate of planulae)

  -Localized tissue rupture

  -Premature expulsion of larvae

  -Excessive mucous production

- Degree of impact from a spill will be determined by:

  -The oil type

  -How much oil is likely to be mixed into the water column

  -How much weathering of the oil has occurred

High risk

- Intertidal reefs and reef flats, where direct contact with the oil is likely.
- Sheltered, shallow water settings, where high concentrations of oil are likely to persist.
- Where leaching from adjacent area creates a chronic source of oil exposure.
- Where coral reef communities are already stressed by pollution, sedimentation, thermal quality problems, etc.

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