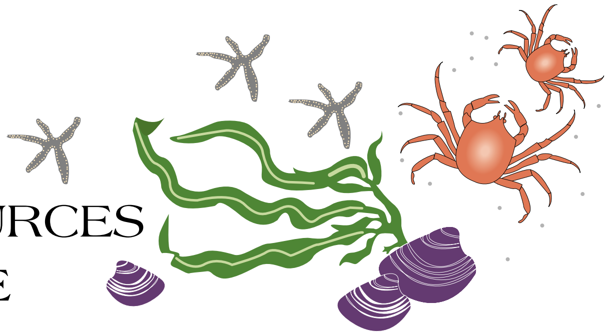
AN INTRODUCTION to COASTAL HABITATS and BIOLOGICAL RESOURCES for OIL SPILL RESPONSE



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An Introduction
to Coastal Habitats and Biological Resources

Introduction

We will discuss the physical, geological, and biological considerations relevant to oil behavior and oil spill response and cleanup. The questions which we will address include:

- How does the physical environment affect the impacts of an oil spill on a shoreline?
- What factors affect the behavior and toxicity of oil?
- What kinds of shorelines are most at risk from an oil spill, and why?
- What are the effects of oil exposure on biological resources?
- What kinds of techniques are available for treatment of oil spills?
- How are the impacts of oil and cleanup assessed and monitored?
- What are the tools that are available for assisting response personnel in evaluating resource impacts?
- What are the important lessons from previous spills?

The response and cleanup techniques that we will discuss have, as their ultimate goal, the minimization of impacts from oil spills. To realize this goal, it is important to have a basic understanding of how each of the components covered in this course interrelate. It is our intent that readers understand the role that each set of considerations—physical, chemical, geological, and biological—plays in determining both the route and degree to which the goal is attained. We will try to pass on the lessons of previous experience and research, and to provide a foundation on which insights and knowledge can be added as time goes on. Ultimately, we hope that this will contribute to an informed and effective oil spill response in coastal waters.

1 The Coastal Environment

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Chapter 1.
The Coastal Environment

Introduction

This chapter presents the physical controls and attributes of coastal habitats as preparatory material for understanding how they may be impacted by an oil spill. The discussion begins with a brief review of the geological forces, such as plate tectonics and continental glaciation, that have shaped the primary framework of the coastal systems. Also given is an introduction to the dynamic coastal processes that shape the detailed configurations of the habitats, as well as a description of the origin and nature of sediment types and water/sediment (and potentially oil) interactions in certain specific environments, such as estuaries and sand beaches.

Coastal Morphology

Introduction

The morphology of a coastline provides the basic framework to which other relevant factors, such as biological habitat and physical processes, are tied. Therefore, a general knowledge of the coastal morphology of the spill site is of primary importance in planning the response to a spill. For example, a young mountain range coast backed by cliffs in bedrock with beaches of coarse gravel presents an entirely different set of problems than does a low-lying coastal plain shoreline with abundant mud flats and salt marshes. The morphology of coastlines is determined by five primary controlling factors:

1) Global tectonic crustal movements

2) Hydrodynamic regime

3) Sediment supply and sources

4) Climate

5) Local geological history and sea-level changes

Each of these controls will be considered separately.

Global Tectonics

A most important aspect of any coastal region is whether it is rising, sinking, or essentially stable—that is, its tectonic setting. In a study of the widths and slopes of continental shelves, Hayes (1964) classified the shorelines of the world into the categories given below:

Class	Tectonism	Examples
A) Tectonic coasts		
1) young mountain range coasts	- Rapid uplift	- California; Alaska; western South America
2) glacial rebound coasts	- Rapid uplift	- Eastern Canada; Norway
B) Plateau-shield coasts	- Relatively stable	- India; West Africa; central Brazil
C) Depositional coasts	- Downwarp	- Gulf and East Coasts of the United States

Definitions of these shoreline classes follow:

<u>Young mountain range coasts</u>: Coastal zone made up of high mountains (maximum elevations greater than 5,000 feet) related to Cenozoic orogenic activity (<±50,000,000 years ago). Bedrock of variable age but principally Tertiary sediments and volcanic rocks. Active tectonic uplift. Mostly short, high-gradient rivers emptying into the sea.

<u>Plateau-shield coasts</u>: Coastal zone made up of plateaus and moderate mountain ranges related largely to pre-Cenozoic orogenic activity. Bedrock composed of ancient basement complexes of granite and gneiss (in shield areas) and Paleozoic, Mesozoic, and Tertiary sediments (in plateau areas). Plateaus formed on complex suites of volcanic rocks are also present and the area is tectonically stable (relative to young mountain range and depositional coasts). Numerous moderately long rivers may be present, depending on climate.

Depositional coasts: Coastal zone made up chiefly of broad coastal and deltaic plains. Bedrock generally Tertiary and Quaternary sediments. Tectonically subsiding area. Many long, large rivers emptying into the sea.

Glacial rebound coasts: Coastlines undergoing uplift because of isostatic readjustment of the earth's crust after removal of the load of the continental ice sheets at the end of the last major glaciation (Wisconsin, 10,000-14,000 years Before Present [B.P.]).

Genetically, these shoreline types are closely related to plate tectonics. The simplest distinction, on the basis of plate tectonics, is between leading edge and trailing edge coasts (Fig. 1-1). Leading edge, or collision, coasts have roughly the same characteristics as young mountain range coasts (as defined above), whereas trailing

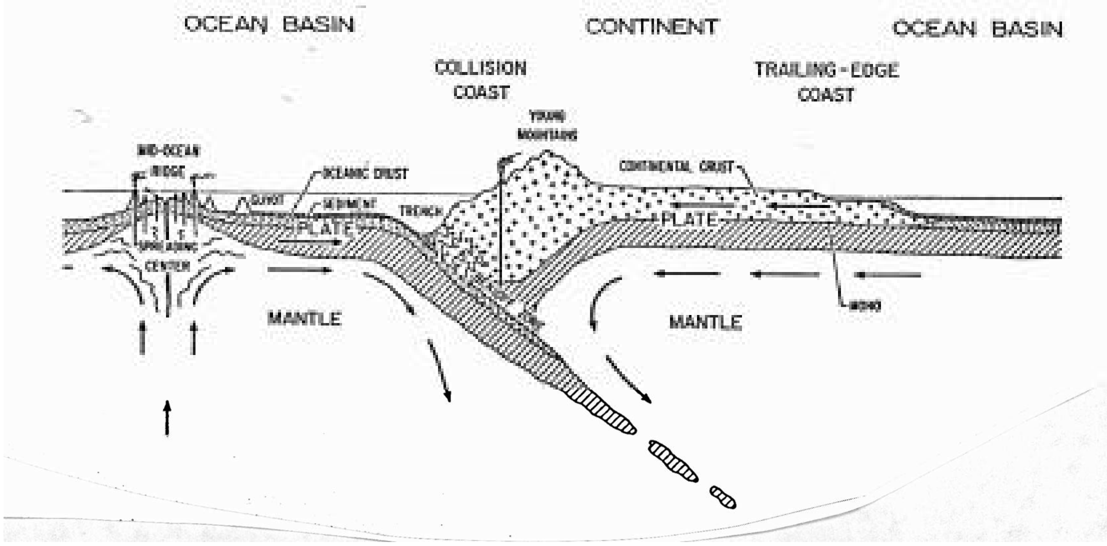

Figure 1-1. Diagrammatic representation of a section through collision and trailing edge coasts. Arrows indicate the direction of movement of crustal plates. (After Inman and Nordstrom, 1971; Fig. 2.)

edge coasts usually have the characteristics of depositional coasts. Inman and Nordstrom (1971) treated this subject in considerable detail and proposed the following major classes:

1) Collision coasts—formed where two plates converge.
    a) Continental collision coasts—where a continental margin is located along the zone of convergence.
    b) Island arc collision coasts—where no continental margin is located along the zone of convergence.
2) Trailing edge coasts—where a plate-imbedded coast faces a spreading zone.
    a) Neo-trailing edge coasts—where a new zone of spreading is separating a land mass.
    b) Afro-trailing edge coasts—where the opposite continental coast is also trailing.
    c) Amero-trailing edge coasts—where the opposite continental coast is a collision coast.
3) Marginal sea coasts—where a plate-imbedded coast faces an island arc.

As a general rule, the collision coasts are characterized by steep, rocky shores and coarse-grained sediments. Wave energy is usually high. Neo- and Afro-trailing edge coasts are of the plateau-shield variety, usually being very complicated shorelines with scattered pocket beaches, some cliffed shorelines, and a variety of other features. Amero-trailing edge coasts and marginal sea coasts are usually dominated by coastal plain shorelines composed of river deltas and barrier islands. Most of the East and Gulf coasts of the USA shoreline fall in the Amero-trailing edge category. The coasts of Washington, Oregon, California, and the south coast of Alaska are continental collision coasts. Much of the rest of the Alaskan coast is a complex marginal sea coast.

Hydrodynamic Regime

Introduction

Following the pioneer work of W.A. Price (1955), we have concluded that the most important control of the morphology of coastal plain shorelines (primarily found on trailing edge and marginal sea coasts) is the type and amount of hydrodynamic energy expended within an area; furthermore, with some exceptions, the two energy factors of most significance, wave energy flux and tidal energy flux, can be related directly to **tidal range**. Davies (1964) and Hayes (1965) classified shorelines, as follows, on the basis of tidal range:

Class	**Tidal Range***
Microtidal coasts	0-2 m
Mesotidal coasts	2-4 m
Macrotidal coasts	>4 m

*To be exact, Davies' boundaries were 0-6 ft, 6-12 ft, and >12 ft, and Hayes' were 0-5 ft, 5-10 ft, and >10 ft. We have rounded off these numbers to the nearest whole metric unit. On the basis of study of details of coastal morphology on the coast of North America, we feel there is much justification for considering changing the mesotidal boundaries or perhaps splitting the mesotidal class into two categories; however, the boundaries proposed above will be maintained in these notes.

Generally speaking, coastal plain shorelines with small tidal ranges (microtidal) are dominated by wave energy, and coastal plain shorelines with large tidal ranges (macrotidal) are dominated by tidal currents and tidal-level fluctuations.

The reasons for this emphasis on tidal range is the fact that the effectiveness of wave action diminishes (i.e., waves cannot break in a concentrated area for a long period of time), and tidal current activity increases as the vertical tidal range increases. Of course, a small tidal range does not insure high wave energy, inasmuch as wave energy varies according to the fetch, average velocity, and duration of onshore winds in an area, as well as the incident swell.

On the basis of a study of coastal charts of the world (conducted at the Defense Research Laboratory, University of Texas), Hayes has compiled the distribution of coastal features versus tidal range. The distribution patterns of seven coastal features are shown in Figure 1-2. Note that river deltas and barrier islands are best developed in microtidal regions, whereas offshore linear sand ridges (built by tidal currents), tidal flats, and salt marshes are most abundant in macrotidal regions. Tidal deltas and tidal inlets are most abundant on mesotidal coasts. Further generalizations can be made about the interaction of wave parameters and tidal range. In fact, it is possible to designate three coastal plain shoreline types [(1) wave-dominated coasts, (2) mixed-energy coasts, and (3) tide-dominated coasts] on the basis of this interaction. Usually, wave-dominated coasts are microtidal; tide-dominated coasts are macrotidal; and mixed-energy coasts are mesotidal. There are

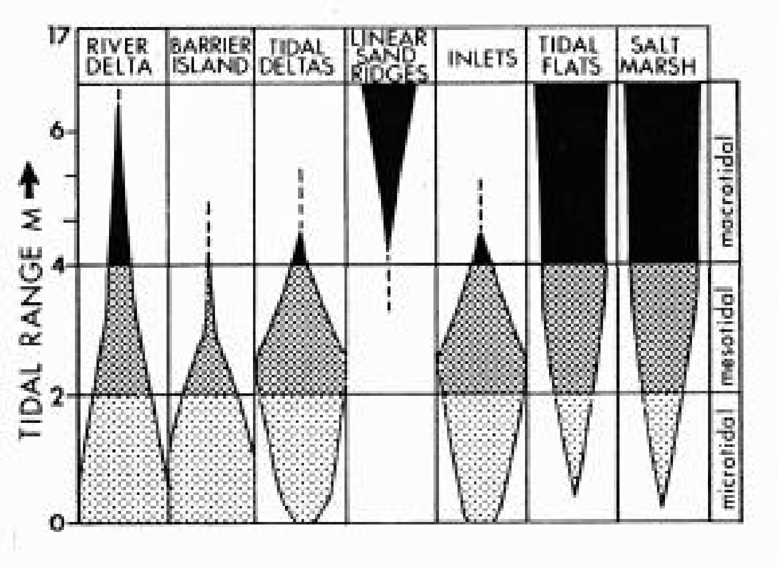

Figure 1-2. Variation of morphology of coastal plain shorelines with respect to differences in tidal range. (From Hayes, 1975; Fig. 1.)

exceptions. For example, a microtidal coast with smaller than normal waves may have the morphology of the typical mixed-energy coast (e.g., west coast of Florida). Therefore, it is the ratio of wave-energy flux to tidal-energy flux that ultimately determines the morphology of coastal plain shorelines.

Wave-dominated Coasts

River deltas with smooth, outer margins made up of sandy beaches occur at the mouths of major rivers on wave-dominated coasts. Between major rivers, long uninterrupted barrier islands are commonplace. Examples of coasts of this type include the Gulf Coast of the United States, the southern Baltic, southern Australia, and many other areas located on enclosed tideless seas, such as the Baltic and Mediterranean. These coasts are usually of the “barred coast” type; that is, a series of break-point bars parallel the beach. Sediment patterns of this model show a simple gradation in grain size from coarse to fine away from shore as a result of decreasing bottom agitation by waves with increasing water depth.

Tide-dominated Coasts

Along coasts occurring at the tide-dominated extreme of the hydrodynamic spectrum, the morphology at major river mouths consists mostly of open-mouthed estuaries. Deltas and barrier islands are inhibited in areas with large tidal ranges because of the tremendous erosive and transporting capacity of currents generated by the tides. Where deltas are present, they are usually of the multilobate type (e.g., Ganges-Brahmaputra Delta). Between major rivers, the coast is occupied by extensive salt marshes and tidal flats. Barrier islands are completely absent. Examples of this coastal type occur in northeast Australia, western Korea, the upper Bay of Bengal, the northern end of the Gulf of California, Cook Inlet, Alaska, the Wash (England), and at many other localities with tidal ranges greater than 4 m. Generally speaking, sediment patterns on coasts of this type are exactly opposite to those on wave-dominated coasts, inasmuch as finest sediments occur on mud flats of the upper intertidal zone, and coarsest sediments occur further offshore in zones where tidal currents prevail.

Mixed-energy Coasts

The intermediate type of coast on the hydrodynamic spectrum, where tidal energy flux and wave-energy flux are relatively equal, is the most complex of the three models. Modern examples include the South Carolina/Georgia coasts of the United States and the Wadden Sea coast of northwest Europe. Deltas are less well developed in this setting than on wave-dominated coasts. Between rivers, the barrier islands are short ("stunted"), and inlets are wide to allow for the large water exchange through the tidal cycle. Tidal deltas are large and numerous due to the occurrence of both strong tidal currents and wide inlets between the barrier islands. Sediment patterns are very complex, being controlled by the combination of wave action and tidal currents. The general model for this type of coastline is illustrated in Figure. 1-3.

Sediment Supply and Sources

Introduction

The nature of the beaches on many coastlines is highly dependent upon the volume and composition of sediments supplied to that shoreline. Where sediments are in abundance, beaches tend to accrete, building seaward, but where they are in short supply, beaches tend to erode, commonly causing damage to man-made structures built along the beach. Therefore, the <u>zone of sediment supply</u> is an important component of the coastal environment, and any change in it would greatly effect the evolution of the coastline. In most areas, the dominant source of sediments within

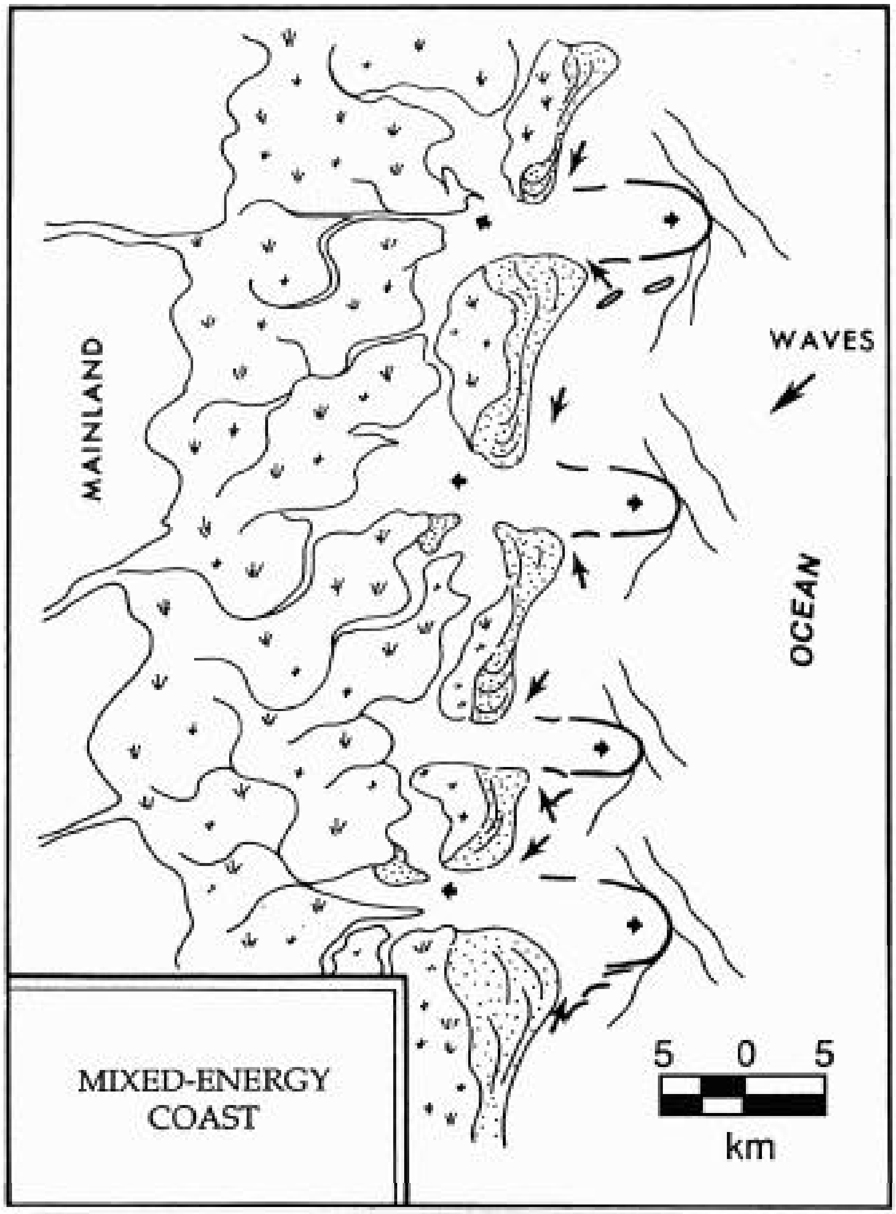

Figure 1-3. Characteristic morphology developed on a coastal plain shoreline (between major rivers) that has a mesotidal range (2-4 m) and average wave conditions, a mixed-energy coast. (From Hayes and Sexton, 1989; Fig. 44.)

the zone of sediment supply is the drainage network that carries sediments from the land areas to the shoreline. Other possible sources include: (a) material brought to the beach from remote segments of the coastline by longshore sediment transport; (b) erosion of rocky headlands or other portions of the shoreline adjacent to the beach; and (c) offshore marine sources, such as coral reefs, chemical precipitates, and shell-bearing organisms. Any of these potential sediment sources can be impacted by the activities of man. Studies on the coasts of California (Inman and Frautschy, 1966), Japan (Watanabe and Horikawa, 1983), and South Carolina (Hayes and Sexton, 1989) show that dams constructed along rivers that supply sediments to the shoreline have trapped large volumes of sand, causing severe beach erosion in those areas. Natural changes frequently impact the zone of sediment supply, as well, as the following two examples illustrate.

> **Mississippi River delta**. - The character of the shoreline around the Mississippi river delta complex varies considerably, dependent upon nearness to the major distributaries of the river. Today, the main channel of the river is building a large birdfoot delta out onto the continental shelf. At positions formerly occupied by the major distributaries, however, the abandoned delta lobe is subsiding and the shoreline is eroding at rates exceeding 10's of meters per year (Penland and Suter, 1983), and a system of barrier islands is forming. There are several abandoned lobes on the delta, each of which continues to erode. Therefore, whole environmental complexes come and go at the whim of the shifting distributaries of the delta.

> **Icy Bay, Alaska**. - Our field work in Alaska indicates that the shoreline west of Icy Bay is undergoing rapid erosion (over 1,000 m between 1900 and 1970; Hayes et al., 1973). This is presumably the result of the fact that a large glacier system, the terminus of which formerly occupied a position parallel to the present shoreline, had retreated over 40 km up inside the bay between 1900 and 1970. The whole character of the shoreline was altered dramatically as a result of this abrupt change in sediment supply. The termini of glaciers are a rich source of coastal sediments in southeastern Alaska.

River Deltas

The most striking manifestation of the impact of the zone of sediment supply upon shorelines is where a major river delta forms at a river mouth. This irregular progradation of the shoreline at the mouth of a sediment-laden stream may or may not conform to the "classic" shapes defined by such river deltas as the Nile and the Mississippi, depending on how the sediment mass is modified by marine processes. In order for the prograding delta form to have been developed on the modern ocean shoreline, the alluvial valley eroded during periods of lowered sea level during the ice ages must be aggraded to above sea level beyond the present shoreline. Where this has not happened, coastal water bodies referred to as estuaries, bays, or lagoons occupy the drowned river valleys. This type of valley flooding is primarily the result of insufficient sediment load of the river, but the process may be aided by tectonic downwarp or strong tidal flow that transports the river sediments offshore.

In their classic summary paper on marine deltas, Coleman and Wright (1975) discussed over 50 parameters that have an impact on river delta morphology. Factors such as characteristics of the drainage basin, river slope, tectonic setting, and coastal climate were acknowledged. Most present-day workers, however, following the original ideas of Price (1955) and Bernard (1965), try to simplify matters by focusing on three basic factors—sediment supply, wave energy, and tidal current energy—in their attempts to define the morphological character of deltas. The ratio of constructive (i.e., sediment supply) to destructive (i.e., waves and tidal currents) processes was used by Fisher et al. (1969) to classify deltas. Galloway (1975) placed this concept on a ternary diagram, with sediment supply, wave-energy flux, and tidal-energy flux comprising the three end members.

Galloway's (1975) classification of river deltas in the marine environment is given in Figure 1-4. River-dominated deltas are characterized by lobate protrusions into the offshore area, such as the modern "birdfoot" delta of the Mississippi River. At river mouths where the sediment output is overwhelmed by the hydrodynamic processes at the shoreline, entirely different delta configurations result. Tide-dominated deltas, such as the Colorado River and Ganges/Bramaputra River deltas, have a characteristic funnel shape, with multiple estuarine channels at the river mouths. Wave-dominated deltas, such as the Nile River and Rhone River deltas, have smooth, arcuate to cuspate, sandy outer margins. In some areas, particularly on young mountain range and arid shorelines, steep gradient streams build alluvial fans into coastal waters, creating another type of delta called a fan delta. The nearshore zones of these deltas are characteristically steep and the beaches are usually coarse-grained sand and gravel.

The zone where the river's waters and suspended sediment load enters the marine environment is characterized by complex flow and mixing patterns. Oil spilled into this zone is usually subject to mixing with the water mass and interaction with the suspended sediments (see discussion of Santa Barbara spill in Appendix A). An example of one of the many ways riverine and ocean waters mix at river mouths is given in Figure 1-5. The type of mixing illustrated in this diagram, usually occurs at a major river mouth in a microtidal, relatively low wave-energy setting (e.g., one of the distributary mouths of the Mississippi River). The term buoyant effluent is applied to this type of river outflow. Wright (1985; p. 28-29) described the process

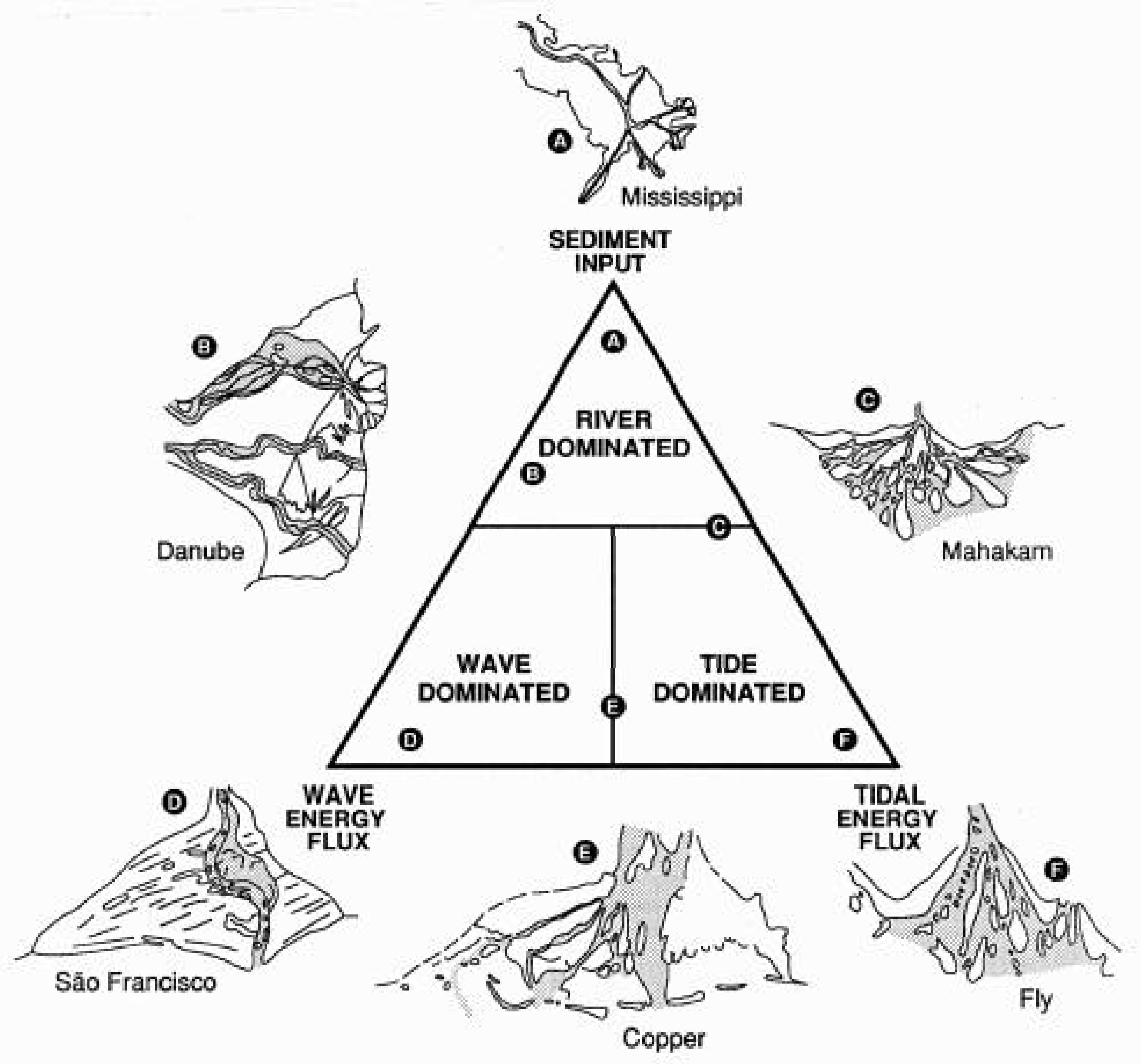

Figure 1-4. Classification of river deltas in the marine environment on the basis of sediment input, wave-energy flux, and tidal-energy flux. (From Galloway, 1975; Fig. 3.)

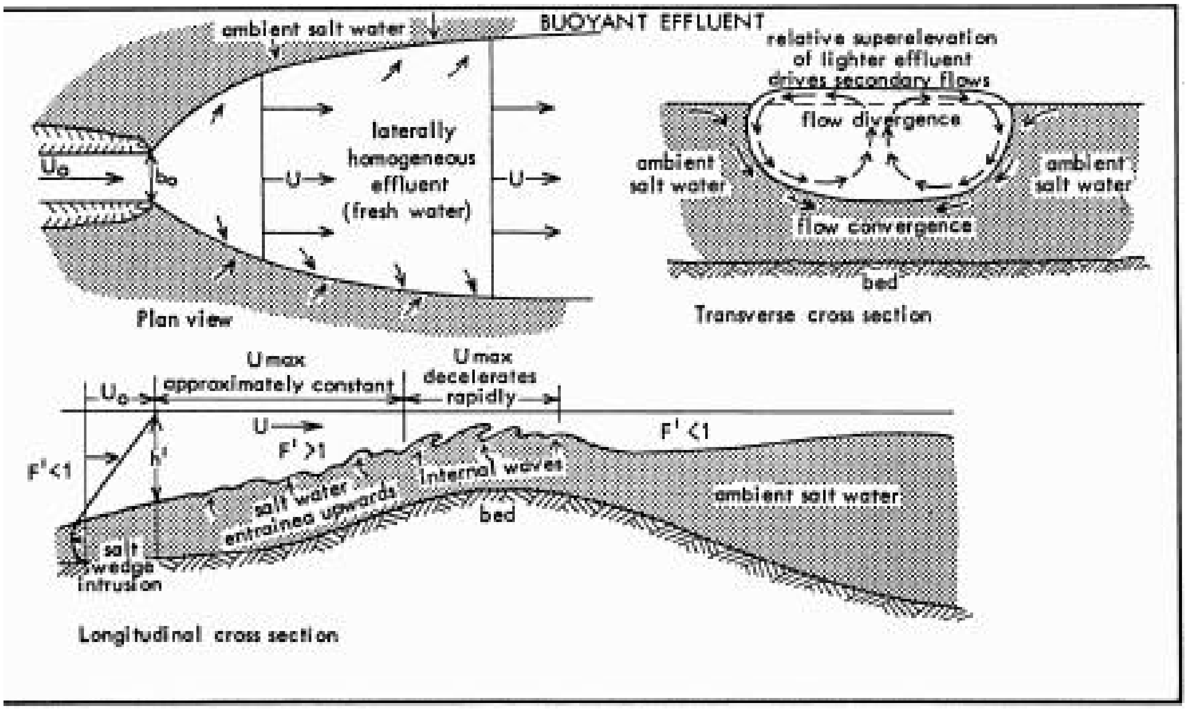

Figure 1-5. Spreading, mixing, deceleration, and secondary flow patterns of buoyant river-mouth effluents. Based on the Mississippi River mouth model. (From Wright, 1977a.)

as follows:

> "Visually dramatic and important features of buoyant effluents are pronounced frontal boundaries and related three-dimensional internal circulation patterns. ...Plume fronts are exceptionally sharp. ...Flow (V) divergence from the centerline of the buoyant effluent near the surface converges at the frontal boundaries with inward-directed saltwater transport from outside that plunges beneath the sloping pycnocline*. (Fig. 1-5) Flow in the lower part of the buoyant effluent is also directed inward. The net result of the combination of flow divergence near the surface and flow convergence near the pycnocline is the development of the dual helical cells illustrated qualitatively"... in Figure 1-5.

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*Boundary marking a sharp change in water density, as at a fresh-water/salt-water interface.

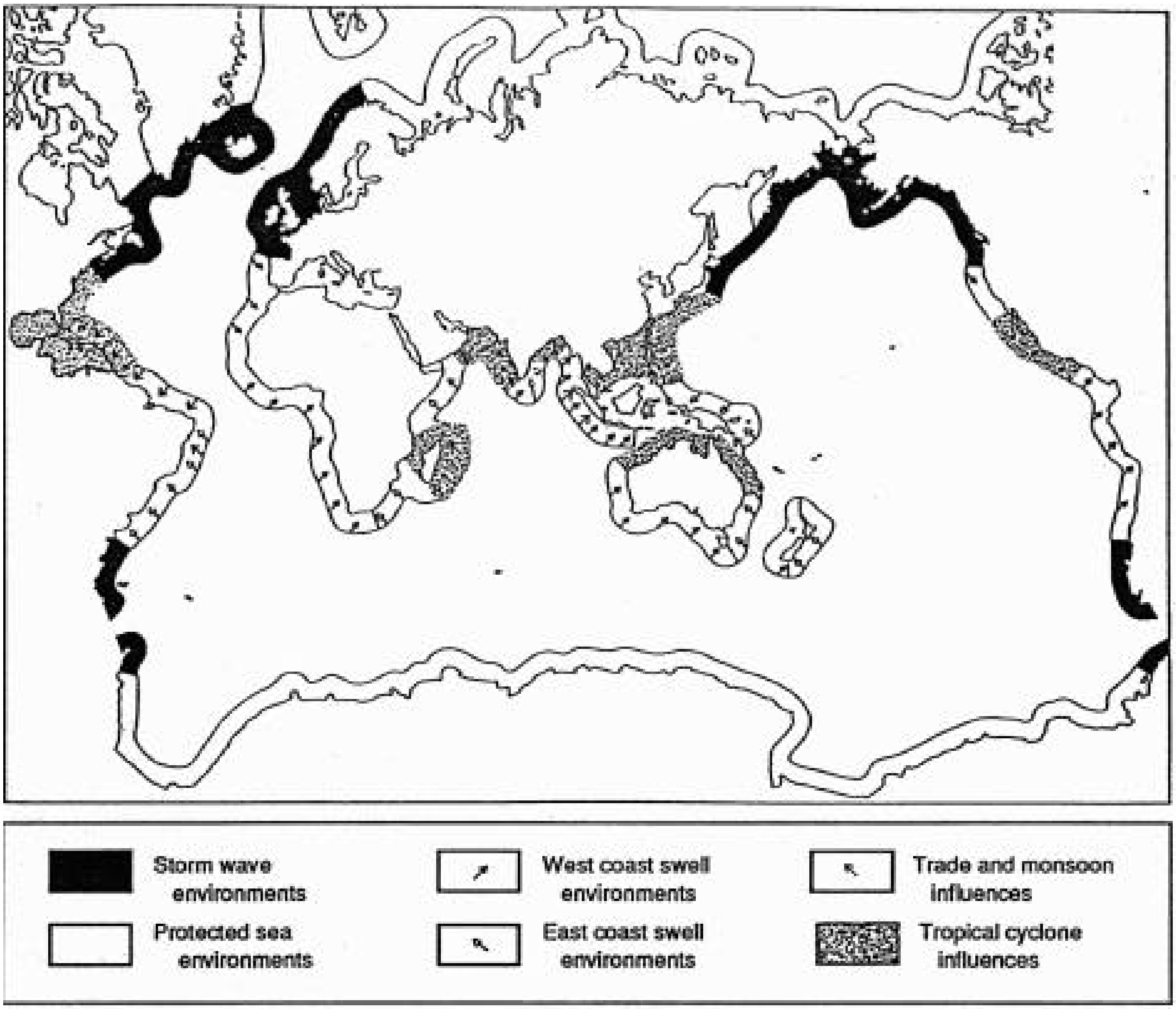


Figure 1-6. Major world wave environments. (From Davies, 1973; Fig. 27.)

Climate

Climate is an important factor in the shaping of coastal environments in that wave conditions, the occurrence of storms, and certain aspects of sediment production and supply can be related to it. Wave climate is controlled principally by global wind and storm patterns (see Fig. 1-6). Needless to say, the production of carbonate materials in the tropics and ice impingement on the shorelines of polar regions are also important climatic considerations. Vegetation type, also primarily related to climate, has an important effect on coastal sedimentation in some areas.

The role of climate in sediment production and supply for the continental shelf, and concurrently in the nearshore coastal zone, was investigated by Hayes (1967). It was found that:

1) Mud is most abundant off areas with high temperature and high rainfall (humid tropics).
2) Sand is everywhere abundant and increases to a maximum in intermediate zones of moderate temperature and rainfall and in arid areas of all, except extremely cold, temperatures.
3) Coral is most common off areas with high temperatures.
4) Gravel is most common off areas of low temperatures (subpolar and polar).
5) Rocky bottoms are generally more abundant in cold areas, but their distributions correlate strongly with tectonism of the adjacent land mass.
6) Shell distribution is not diagnostic with regard to climate.

Three primary climatic factors are thought to be responsible for these patterns. The type of weathering (chemical or mechanical) taking place in the source areas is of major importance in that it determines the availability of sediment types to streams (e.g., mud is most abundant off areas with intense chemical weathering). The presence or absence of major rivers (controlled by amount of precipitation) determines the volume of Holocene sediments being carried onto the shelf; hence sand is dominant on the inner shelves of arid areas due to the absence of river-transported mud. Deposition of coarse (gravel) sediments is virtually restricted to polar and subpolar areas, where they are deposited as the result of glaciation and ice-rafting. Other factors, such as source stream gradient and hydrodynamic energy, exert strong local influence, but are thought to be less important than the above climatic factors in determining world-wide, sediment distribution patterns.

Local Geological History and Sea-level Changes

The aspect of local geological history of shorelines related to plate tectonics was discussed above. When responding to an oil spill, the detailed local geological history of the spill site should be considered carefully. For example, areas that were glaciated during the Pleistocene, such as the coastlines of New England, Puget Sound, and the Great Lakes, have complex local configurations related to the passage of the ice. Shorelines produced by erosion of glacial till deposits differ markedly from flooded glacial scours, eroded outwash shorelines usually are associated with extensive sand-beach systems, and so on. Local faulting and earthquake history also leave an indelible mark on leading-edge coasts such as California and Alaska. The *Exxon Valdez* spill impacted some shorelines that had been uplifted (as much as 10 m) and some that had been downdropped (as much as 2 m) during the Good Friday earthquake of 1964. Several differences in spill behavior were noted on the opposite sides of the fault zone (Michel and Hayes, 1991).

Another important historical factor is the changes in sea level that have occurred relative to the last ice ages. It is generally conceded that sea-level dropped more than 100 m during the Wisconsin glaciation (Milliman and Emery, 1968). Beginning around 17,000 BP (Laville and Renault-Miskovsky, 1977), sea level probably rose rapidly to near its present level around 6,000 BP. A generalized sea-level curve for that time period is given in Figure 1-7. Details on the more minor variations in sea level that have occurred during the relative stillstand of the past 6,000 years have been greatly refined by excellent collaborative efforts by archeologists and geologists (e.g., DePratter and Howard, 1980; Colquhoun et al., 1981). The sea-level curve that has been derived for this time period on the South Carolina coast is given in Figure 1-8.

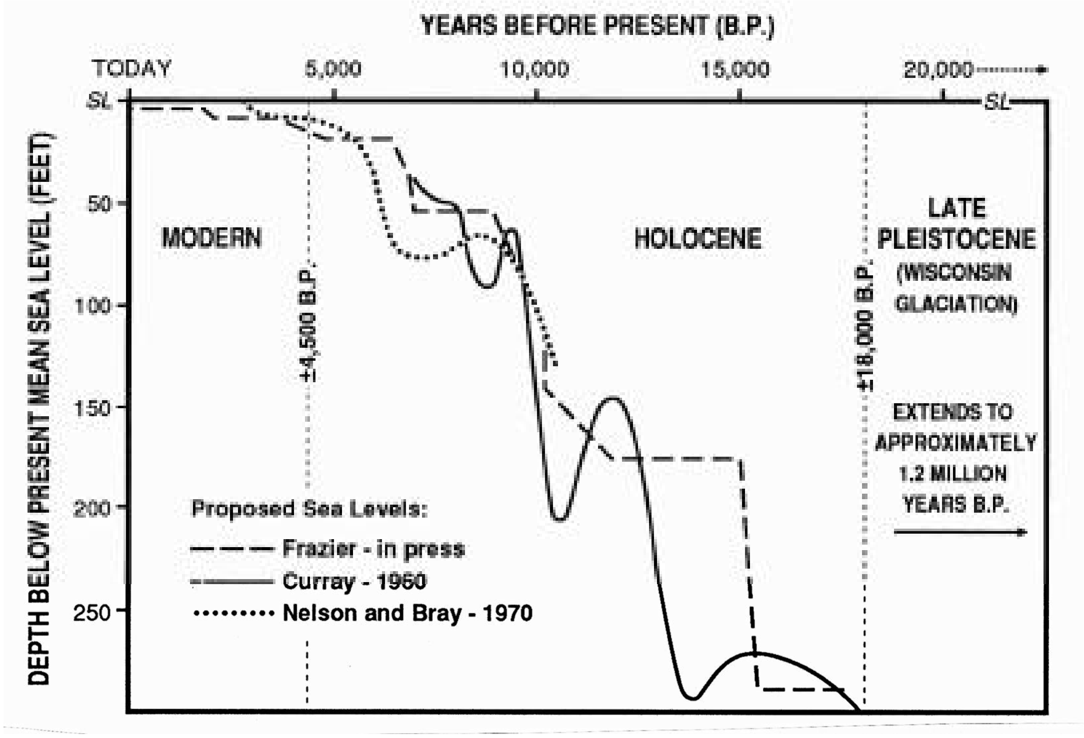


Figure 1-7. Proposed sea-level changes during the last 20,000 years for the Gulf Coast area. (From Fisher, et al., 1973; Fig. 5C.)

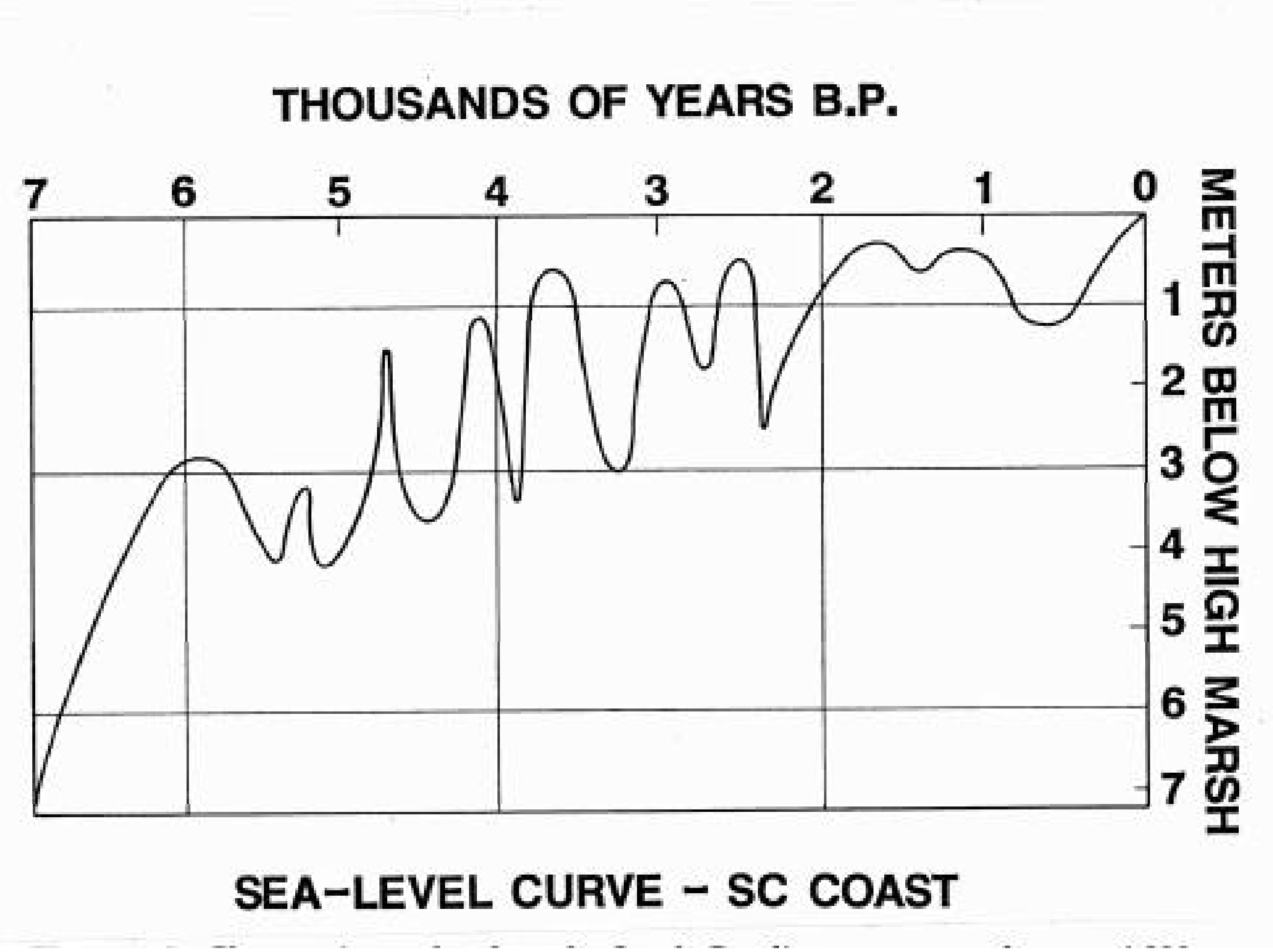


Figure 1-8. Changes in sea level on the South Carolina coast over the past 6,000 years, based on detailed, combined archeological and stratigraphical research. (Modified after Colquhoun et al., 1981 and Colquhoun and Brooks, 1986.)

Dynamic Coastal Processes

This section is a brief introduction to the important dynamic coastal processes that affect an oil spill site, including winds, waves, tides, and currents.

Winds

Probably the most important factor in dispersal of an oil spill is the effect of the wind. The importance of this factor was clearly illustrated during the spills of the *Amoco Cadiz*, *Florida*, *Bouchard No. 65*, and *Puerto Rican*, among others. During the *Amoco Cadiz* spill, consistent westerly winds over 20 km/hr accounted for a west-to-east dispersal of the oil and an initial uniform coating of the westward-facing shore during the first two weeks after the spill. The wind changed on 2 April and blew consistently from the northeast until 10 April. It was these northeast winds, aided by tidal currents, that dispersed the oil to the west and south, polluting previously unaffected eastward-facing coasts (Gundlach and Hayes, 1979).

Waves

Introduction

Waves are important at an oil spill site in that they:

1) May inhibit cleanup activities by creating rough seas.

2) Disrupt or inhibit booming activities.

3) Mix oil into the water column.

4) Erode the beach.

5) Cleanse beach sediments of oil.

The occurrence of wave environments on a worldwide basis is given in Figure 1-6. The highest wave energy is found in the storm-wave environments. High-to-medium wave energy is experienced on west coasts of continents in swell environments; wave energy varies from low to medium-high on east coasts of continents in swell environments. In major enclosed seas and along Arctic and Antarctic coasts, mean wave energy levels are low (Davies, 1973).

Most of the wave energy arriving at the shoreline is contained in progressive waves generated by winds blowing over the water. They are termed progressive waves because they move in the general direction the wind is blowing. These waves have two common forms: seas and swell.

Seas

Seas are highly irregular waves with pointed crests which are produced and influenced directly by the wind blowing over the water. They generally include a wide range of wave lengths and periods, making it difficult to describe the average wave. The height of waves at a given water depth depends on three factors: wind velocity, fetch (the waterway distance over which the wind blows), and wind duration (length of time a given wind velocity occurs). As each of these factors increases, wave heights increase.

Swell

When the wind stops blowing, seas become more rounded and smooth in appearance, approaching a sinusoidal shape. Such waves are called swell. Because the velocity depends on the period or wave length, swell waves tend to sort themselves out naturally at sea, traveling in groups with approximately equal velocity. Typically, the sea surface contains a complex pattern of locally generated seas interacting with swell from another part of the ocean.

Waves at the Shoreline

Seas and swell are transformed as they approach the coast because of the effect of friction as the depth of water decreases. If waves approach at an angle to the shore, they will bend (refract) toward the shore. Also, they will generally decrease in height because of shoaling and friction with the sea floor. Waves break when the depth of water is approximately equal to the height of the wave. Thus, a wave one meter high will usually break in about one meter of water.

Breaking Wave Types

There are three basic types of breakers which occur on beaches, mainly depending on beach slope (Fig. 1-9). Along gently sloping beaches, spilling waves are most common. These waves have a broad foam area at the wave crest as they

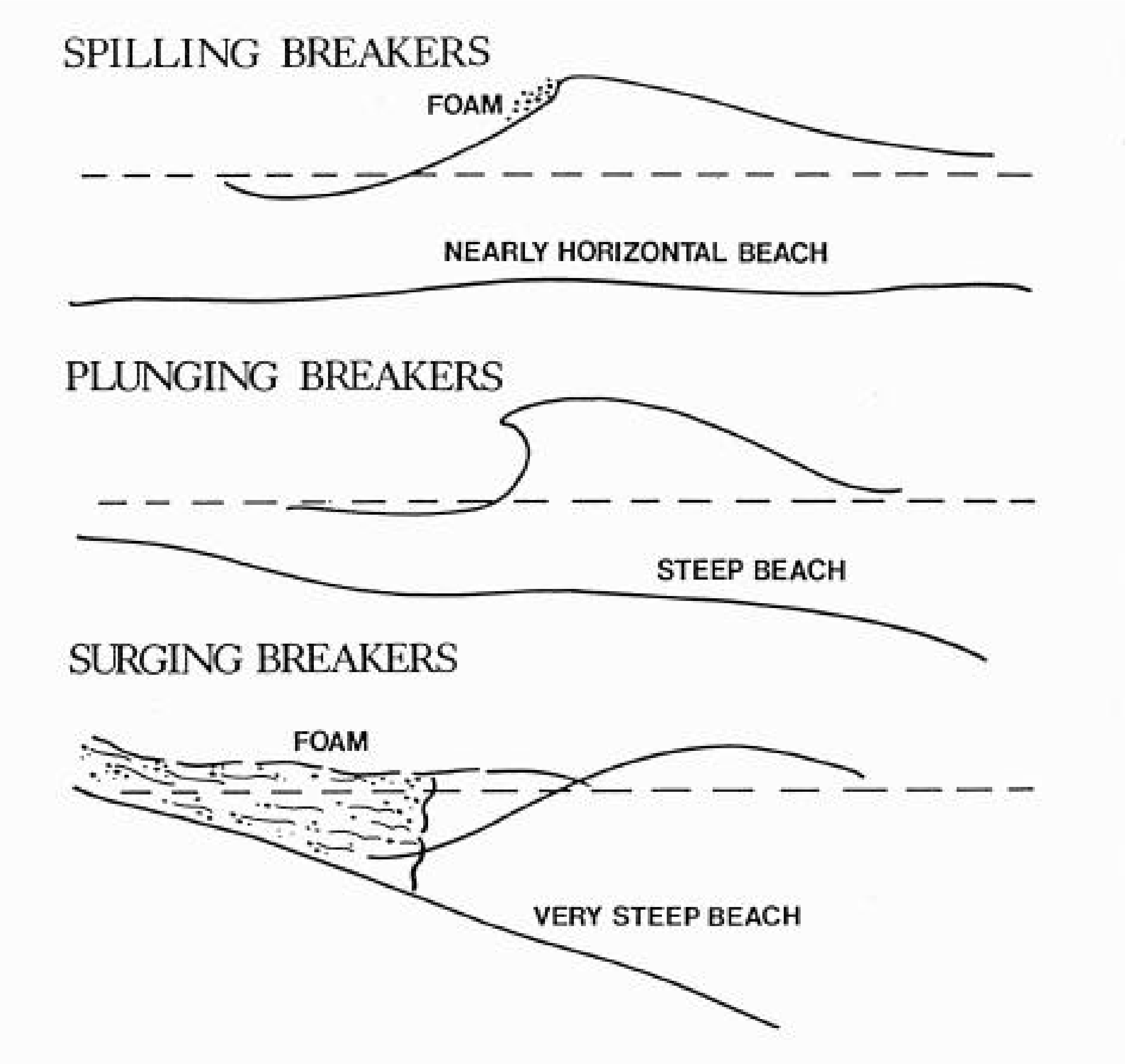


Figure 1-9. The three principal types of breaking waves that occur on the beach. (From Komar, 1976; Fig. 4-17.)

approach the beach, expending their energy over a relatively wide surf zone. As a rule, they tend to move sand onto the beach. Plunging waves occur as beach slope increases. They have curling breakers which entrain a vortex of air as they break. They are more violent than spilling waves and expend their energy rapidly over a narrow width of the surf zone. As a rule, they entrain more sediment than spilling waves and commonly tend to move beach sand offshore to the limit of the outer breaker line. Surging waves occur on steep slopes and are characterized by sloshing up and down the beach.

Wave Erosion

Steep, plunging waves generally cause shoreline erosion and retreat. A schematic representation of storm waves eroding a beach is given in Figure 1-10. Beaches typically erode during storms and recover to near-original profiles during intervening periods. In a few areas, such as the southern California coast and the monsoon-impacted coast of Oman, a seasonal beach cycle is present (winter erosion in California and summer erosion in Oman!).

Local Variations in Wave Energy

Wave energy is not distributed evenly along some shorelines. Usually, this is the result of wave refraction around an offshore island or rocks, over submerged bathymetric highs or lows, or as the result of a variable orientation of the coast.

The uneven distribution of wave energy along local shorelines (scale of a few kilometers) has been demonstrated in many areas. Two well-known examples, the coast of southern California and the Delmarva Peninsula, illustrate this principle. In southern California, submarine canyons occur close to the shoreline. Waves tend to refract away from the canyon openings, creating areas of decreased wave energy at the shoreline adjacent to the canyon heads. On the Delmarva Peninsula, submerged linear ridges project away from shore in a northeasterly direction. Waves passing over these ridges are focused by wave refraction near the points of intersection of the ridges with the shoreface. In both regions, beach erosion is most critical in areas where wave energy is focused by wave refraction.

Tides

The importance of tides in shaping coastal morphology is discussed above. Tides are also important at oil spills in that they: (1) generate currents that disperse the oil and (2) alternately expose and cover intertidal areas impacted by the oil.

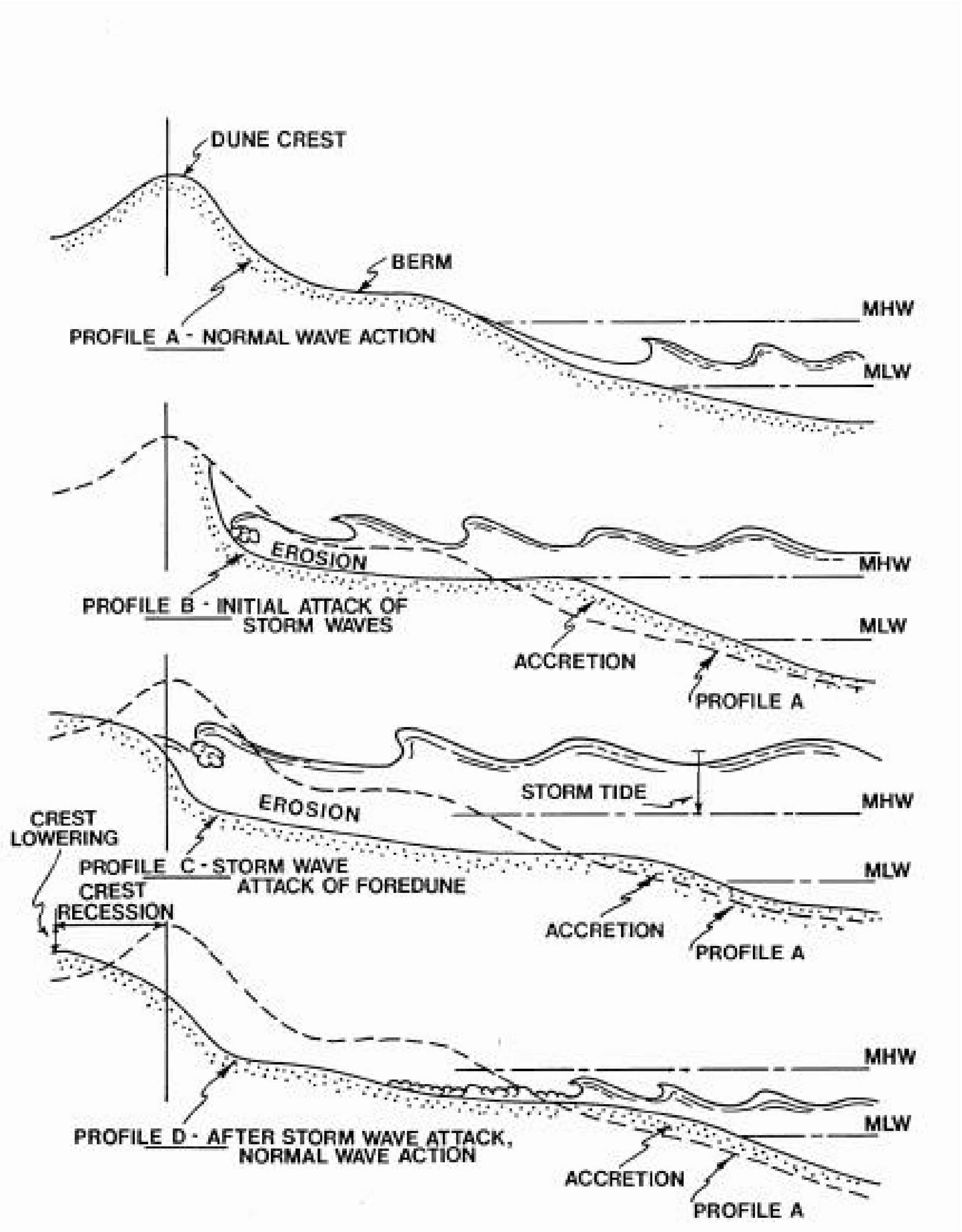


Figure 1-10. Schematic diagram of storm wave attack on beaches. (From CERC 1973; Fig. 1-7.)

The largest tides in the United States are experienced on the coast of Maine and in parts of Alaska (e.g., Cook Inlet and Bristol Bay). Small tides occur along the Gulf and Arctic coasts; medium tides occur along the rest of the U.S. shoreline.

The tides follow a cycle which is controlled by the position of the sun and moon relative to the earth. When the sun and moon are in syzygy (i.e., in line with each other), the tidal range is greatest (spring tides), and when they are in quadrative (i.e., at right angles to each other), the tidal range is least (neap tides). Spring and neap tides occur twice each lunar month.

The most severe erosion of the beach occurs at high tide. During spring tides, higher levels of the beach are exposed to wave action than during neaps, so erosion is at a maximum. This is an important consideration when predicting oil removal from sand beaches by natural processes.

Observations on the east coast of the U.S. by university researchers and the U.S. Army Corps of Engineers show that storms do their greatest damage when they cross the coast during a high spring tide. Observations on the southeastern U.S. coast show that the beach may be erosional during spring tides and depositional during neap tides under similar wave conditions. Erosion occurs at spring tide because (1) the dune ridge is exposed to wave action, and (2) the beach sediment is water-saturated because of the higher level of the sea.

It is important that careful attention be paid to the tides during a spill response, through repeated reference to the daily tidal curves, such as the ones shown in Figure 1-11. Reference must be made to the tidal data in order to: a) plan field surveys in order to utilize the times of maximum exposure of the intertidal zone; b) predict future impacts of exceptionally high or low tides; c) predict possible beach cycle changes; and d) anticipate changes in tidal current velocity and direction.

Currents

Importance at Oil Spills

Large oceanic current systems, such as the Gulf Stream, usually have little effect on coastal-zone oil spills. An exception occurred during the *Exxon Valdez* spill, when the Alaska coastal current carried oil from the spill hundreds of

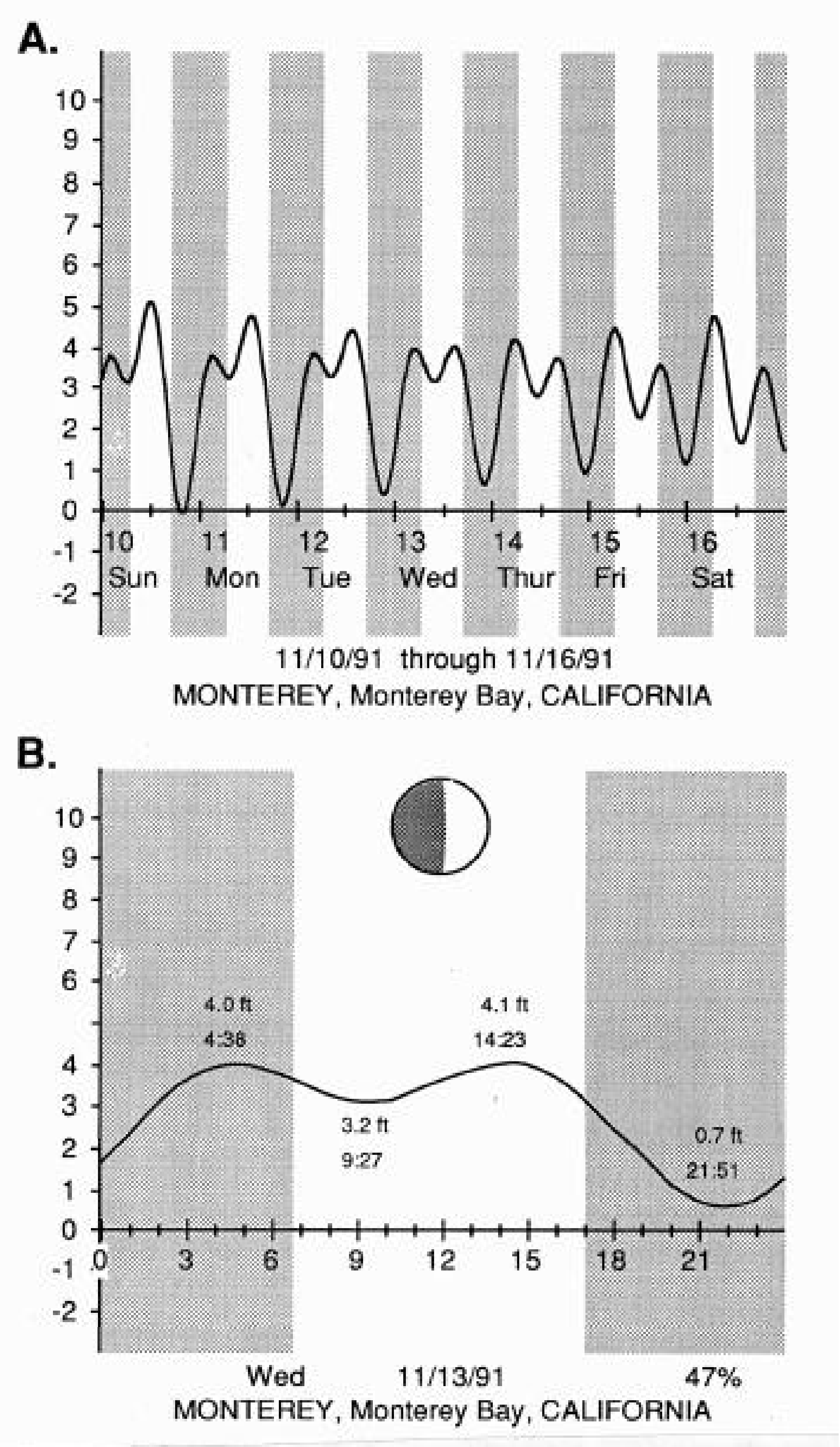


Figure 1-11. Tidal curves for the Monterey Bay, California area. A) The curve for a full week. Note the strong diurnal inequality. B) Curve for a 24-hour period.

kilometers along the coast. The current systems which are usually most important during spills are those induced locally by rivers, tides, winds, and waves.

River-induced currents are almost entirely confined to deltaic and estuarine situations and vary geographically with factors affecting the amount and seasonality of discharge (Davies, 1973; p. 52). During periods of high runoff, these currents would generally tend to keep the oil offshore, but the potential for mixing of oil into the water column should always be considered (e.g., see Fig. 1-5).

Tide-induced currents vary with tidal type and range, tending to be most powerful with semidiurnal tides of large range and least powerful with diurnal tides of small range. Further details were given by Davies (1973; p. 53).

> "Although tidal currents are reversing, inequalities between flood and ebb streams may often be significant in terms of net transport, and on coasts with mixed tides, the normal sequence of highs and lows may be of especial importance in producing such inequalities. Thus, if the sequence is low low water, low high water, high low water, high high water, the two flood currents are essentially equal in magnitude and duration, but the two ebb currents are unequal so that velocities in the great ebb between high high water and low low water may be much greater than at either of the flood stages. Conversely, a sequence of high high, high low, low high, low low gives one exceptionally strong flood current between low low and high high water.
>
> In coastal inlets, the size, and particularly the length, of the inlet may affect the phase relationship between tidal stage and current velocities. Normally, the highest velocities occur at mid-tide, but in long estuaries, there may be considerable divergence so that, near the mouth, low tide may be associated with the fastest ebb and high tide with the fastest flood. This may have a morphologic effect by influencing the height at which strongest currents operate."

In short, these currents can be very complex, thus site specific data are usually required.

Wind-induced currents are highly variable; thus, a constant monitoring of wind conditions at the spill site is necessary for prediction of oil-slick motion.

Wave-induced currents are produced by wave setup along the shore and are basically divisible into longshore currents, resulting from oblique wave approach and running more or less parallel to the shore in the surf zone, and rip currents that move outward from the shore. These types of currents are important in transporting oil and oiled sediments once oil from the spill impacts the beach where it may be either resuspended into the surf zone or become incorporated as part of the sediment mass.

All of the above types of currents combine and interact to produce very complicated current systems in the nearshore zone, as is illustrated for the La Jolla, California area in Figure 1-12. Detailed site-specific data and continued monitoring of wind and tidal conditions are almost always required to accurately predict oil trajectories in the nearshore zone.

Importance to Coastal Sedimentation

Of the different types of currents present, wave-generated currents have the most important influence on open coast beaches. Tidal currents are important in modifying sediment transport near inlets, but have little effect on uninterrupted straight shorelines, except in areas with very large tidal ranges (greater than 4 m). Ocean currents only rarely affect nearshore sediment transport. A notable exception is the Guyana Current, a branch of the North Equatorial Current, which moves large quantities of fine-grained sediment discharged from the Amazon River along the shoreline of northeastern South America (Fig. 1-13).

Wave-generated currents include longshore currents and rip currents. Longshore currents are discussed in Chapter 3. Rip currents flow from the beach seaward and are generally part of a well-defined nearshore cell circulation such as is illustrated in Figure 1-14. The most commonly held theory for the origin of rip currents is that they result from interactions between incoming waves and edge waves trapped within the nearshore system (Komar, 1976). Edge waves are free-wave motions introduced by a coast in its interaction with surges or lower-period oscillations (Bowen and Inman, 1971). They are generally standing waves with crests normal to the shoreline and wave lengths from crest to crest parallel to the shoreline (Komar, 1976; p. 176). Bowen and Inman (1969) demonstrated that longshore variations in wave setup caused by periodic longshore variation in wave height generate lateral flow, with rip currents flowing seaward at the positions of lowest wave heights.

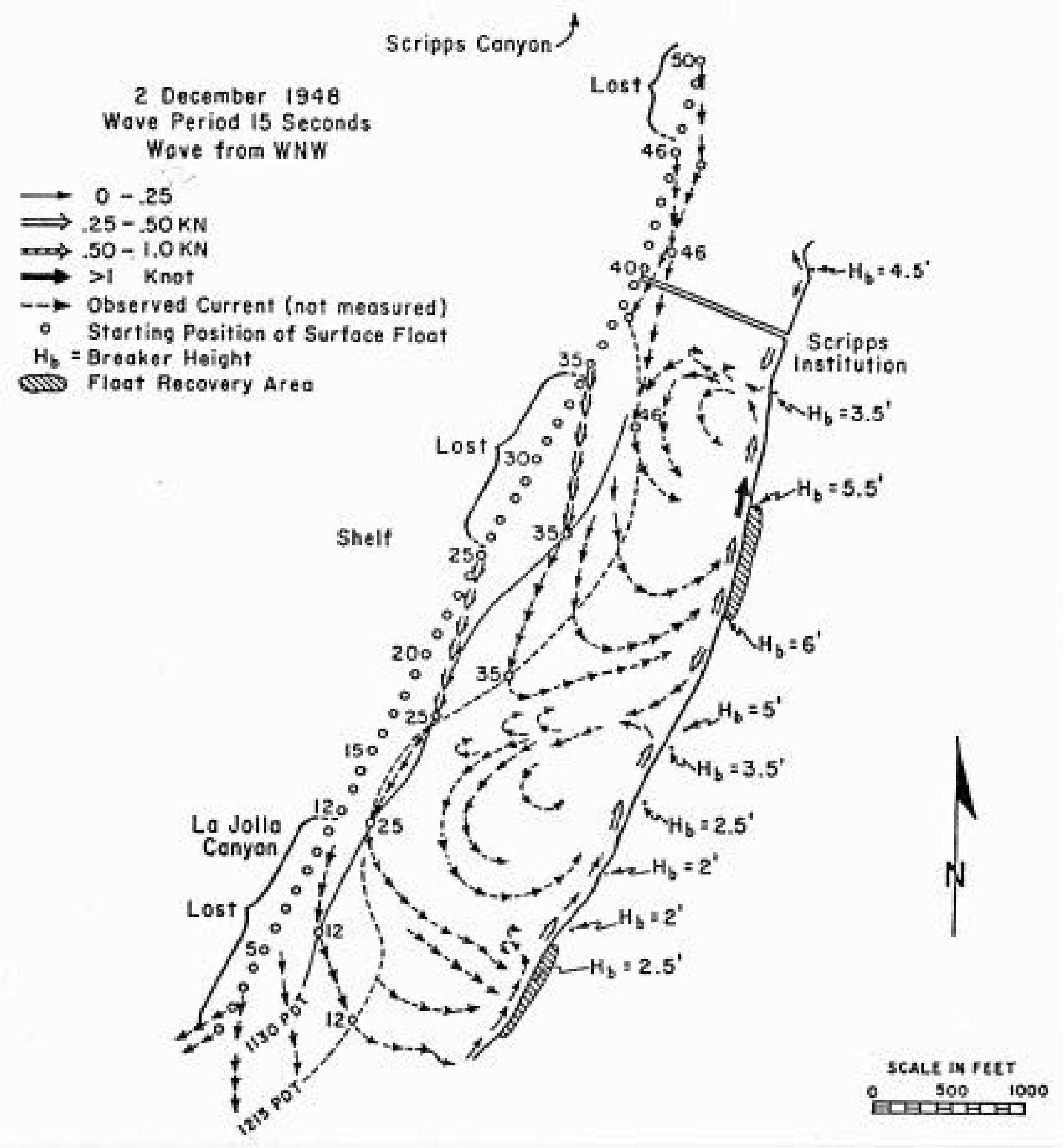


Figure 1-12. Nearshore current sytem near La Jolla Canyon, California on 2 December 1948. (From Shepard and Inman, 1950.)

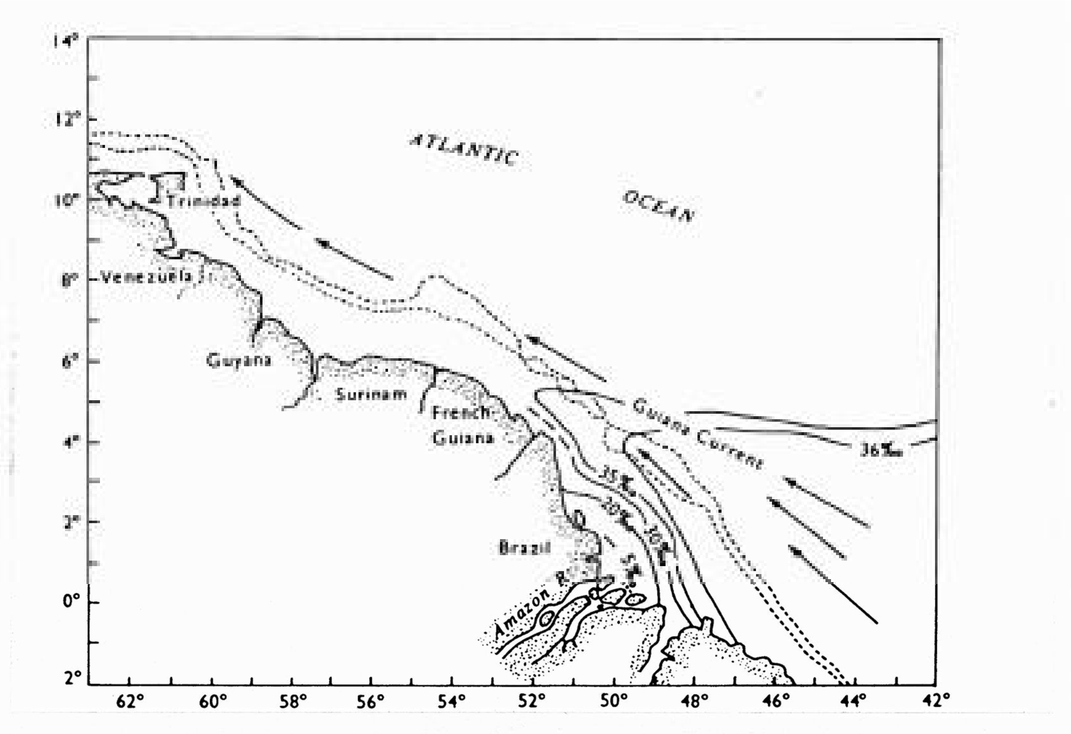


Figure 1-13. Surface currents over the Amazon Delta front. (Based on data of Gibbs, 1980; from Wright, 1985; Fig. 1-28.)

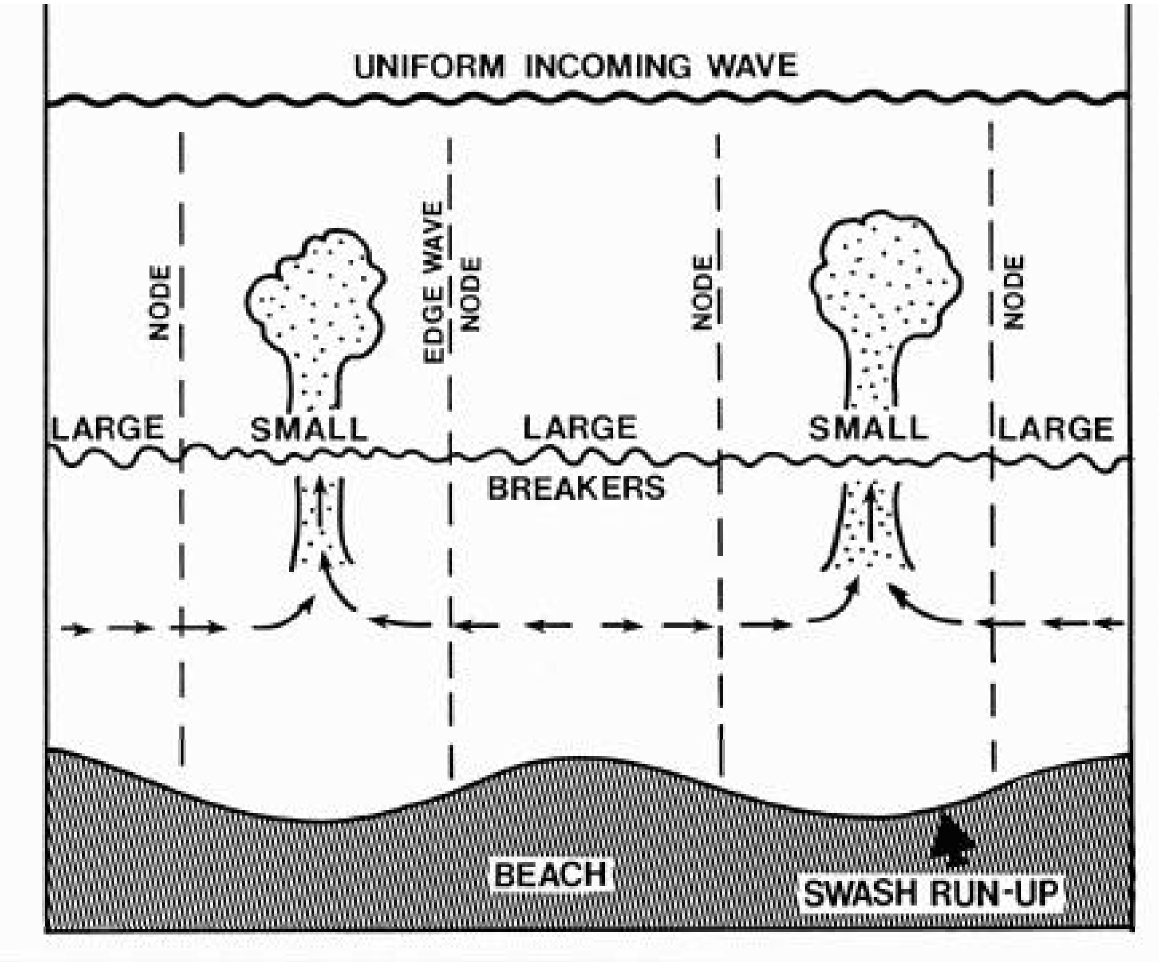


Figure 1-14. Illustration of nearshore rip currents. Note the positioning of the currents where the breaker height is smallest—that is, where edge waves and incoming waves are 180 degress out of phase. (From Komar, 1976; Fig. 7-8.)

Wave heights are least where the edge wave and incoming wave are 180 degrees out of phase (see Fig. I-14; from Komar, 1976). Rip currents carry sediments off the beach during erosional events. The authors have observed rip currents carrying significant quantities of oil offshore during a spill at Cape Hatteras, North Carolina and at the *Peck Slip* spill in Puerto Rico.

Coastal Storms

The most dramatic changes of shorelines occur during major storms, which usually result from the passage of tropical or extratropical cyclones. Much of the eastern and southern shoreline of the United States is affected by a tropical cyclone, or hurricane, every few years (Fig. 1-15). Most of these storms result in extensive coastal flooding, severe beach erosion, and loss of property and lives. A tropical cyclone that occurred on the Texas coast in September 1979 removed much of the oil that had accumulated on the beach as a result of the *Ixtoc 1* spill (discussed further in Chapter 3).

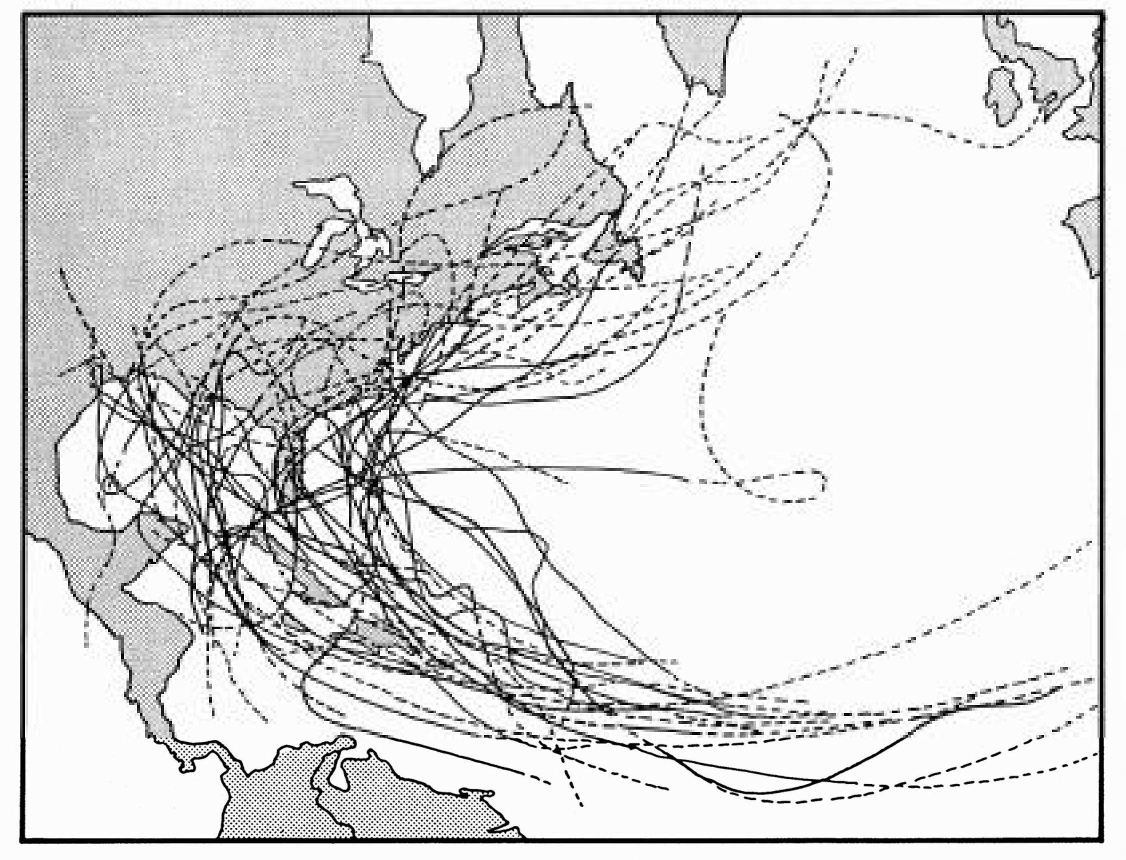


Figure 1-15. Computer plot showing the tracks of a selected number of Atlantic tropical cyclones, 1886 through 1969. (From Neumann and Hill, 1976.)

Extratropical cyclones are the dominant force in initiating beach cycles on the east coast of North America (discussed in Chapter 3). The effectiveness of these storms, which occur several times a year, is determined by: (1) size of storm; (2) speed of storm movement; (3) tidal phase and stage; (4) storm path; and (5) time interval between storms (Hayes and Boothroyd, 1969). Both hurricanes and extratropical cyclones breach barrier islands and create new tidal inlets, a process of concern during a spill response because the new inlets provide an avenue for oil from an offshore spill to reach sensitive lagoonal or estuarine habitats.

The Three-Dimensional Beach

The beach is a three-dimensional body of sediment made from material carried to the site by wave-generated currents which flow both parallel and perpendicular to the shore. On many sandy shorelines, a type of rhythmic beach topography (Homma and Sonu, 1962) develops. This topography has been described for the coasts of the Netherlands (Bruun, 1954), North Carolina (Dolan, 1971), the Great Lakes (Evans, 1939), Cape Cod (Goldsmith and Colonell, 1970), and several other localities. Sonu (1968), who termed the features "cusp-type sand waves", discussed them in detail. He stated (p. 383) that Evans (1939) was probably the first to describe their formation. The total system of rhythmic topography migrates parallel with the shore in the direction of longshore drift at different rates, depending upon the size of the features, the local wave climate, and probably the grain size of the sediment. In the process of formation of rhythmic topography, depositional berms assume cusp-like shapes; however, these cuspate forms are considerably larger than normal beach cusps. The wave lengths of most of the cusp-type sand waves at Cape Hatteras, North Carolina, ranged between 500 and 600 m, and they migrated at rates averaging between 100 and 200 m per month (Dolan, 1971; p. 177). The most important implication of the recognition of the abundance of rhythmic topography, according to Dolan (1971; p. 178), is the fact that "sand beaches cannot be considered in terms of stationary straight lines or simple angles, but must be treated as nonstationary sinuous forms." A sketch of the type of rhythmic topography described by Sonu (1968; 1973) is given in Figure 1-16.

Studies in recent years on the microtidal, sandy beaches of the swell-dominated southeastern coast of Australia have provided a more detailed accounting of the three-dimensional variability of high-energy beaches (Short, 1978; Wright et al., 1979).

The combined work of Short, Wright, and their colleagues on the southeastern coast of Australia gave birth to the concept of morphodynamics, which is defined as the "combination of beach-surfzone morphology and wave-current dynamics" (Short, 1979; p. 553). Short (1979; p. 567) stated that "breaker wave power provides energy to

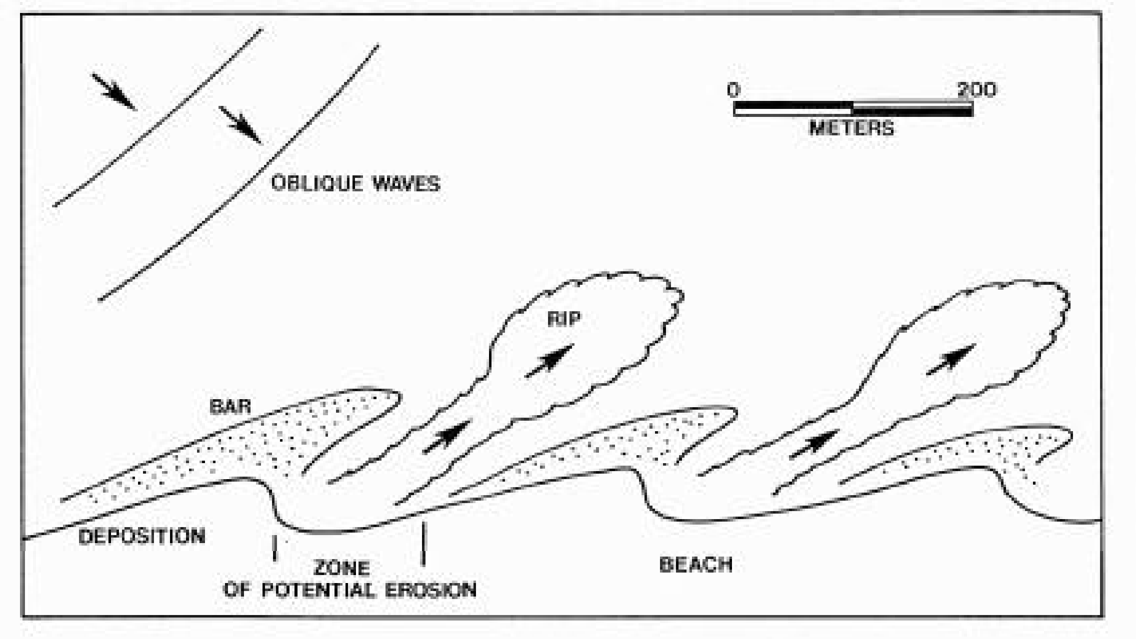


Figure 1-16. Rhythmic beach topography as described by Sonu (1973). The shoreline bulges move in the direction of longshore sediment transport at rates of up to hundreds of meters per year.

move a beach through various beach stages". Wright et al. (1979) placed emphasis on the reflective and dissipative nature of beaches, based on extensive field measurements of surf and inshore current spectra and inshore circulation patterns.

According to Wright et al. (1979; p. 105), reflective sandy beaches are characterized by steep, linear beach faces, well-developed berms and beach cusps, and surging breakers with high runup and minimum setup; rip cells and associated three-dimensional inshore topography are absent. Dissipative sandy beaches are typically found on open coasts and are characterized by concave-upward nearshore profiles and wide, flat surf zones which may contain multiple bars. Waves break tens of meters seaward of the beach and dissipate much of their energy before reaching it. Typical reflective and dissipative beach profiles are shown in Figure 1-17.

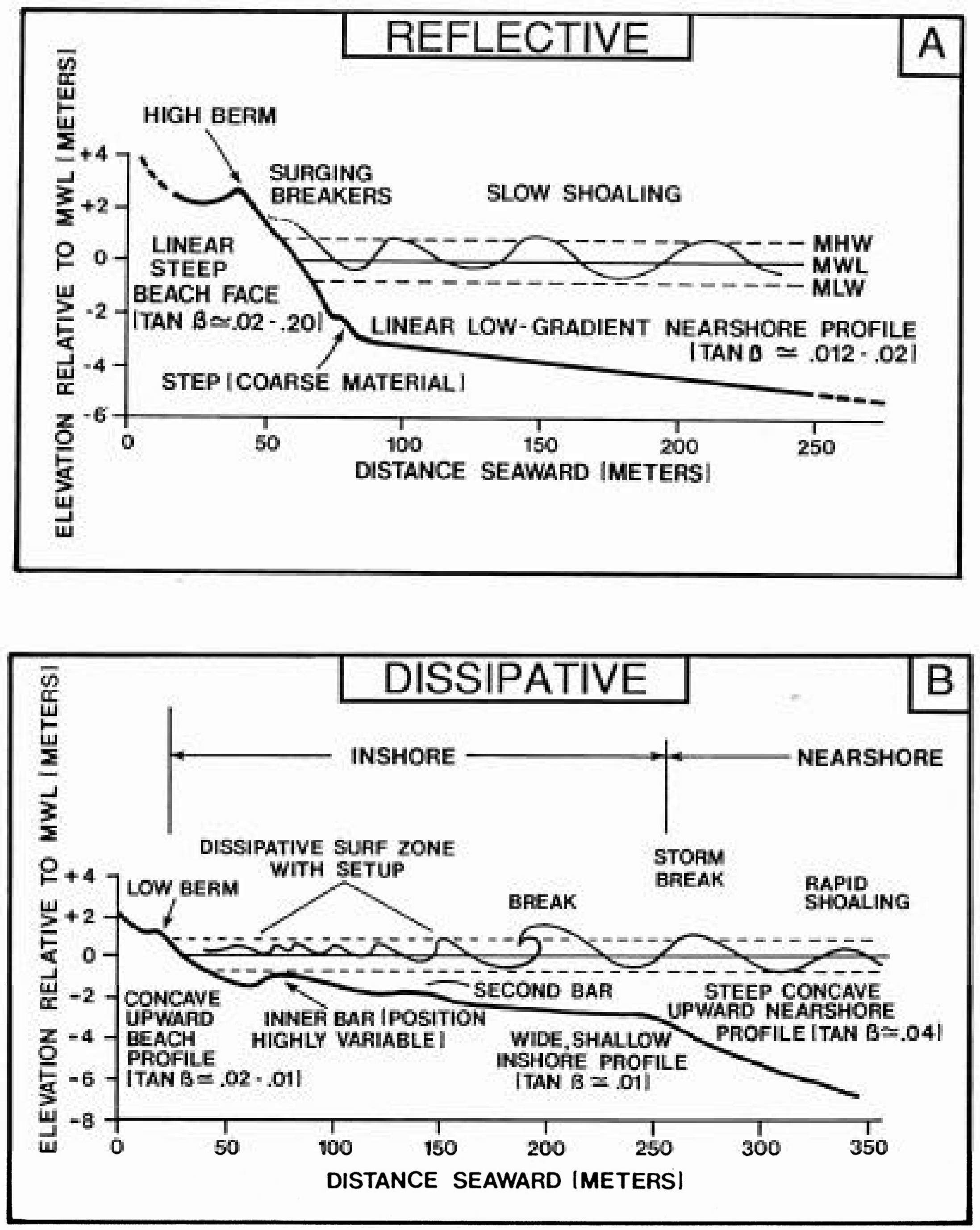


Figure 1-17. Typical cross-sectional profiles of reflective (A) and dissipative (B) sandy beach profiles. (From Wright et al., 1979; Figs. 3 and 6.)

Coastal Sediments

Introduction

The characteristics of the coastal sediments at the spill site are of primary importance. All cleanup programs must be attuned to the nature of the oil/sediment interactions. For example, oil does not penetrate fine-grained sand beaches but may percolate down to several tens of centimeters in gravel beaches.

Sediment Texture

Coastal sediments are classified according to the dominant size of the individual clasts into three general categories: 1) gravel, mean size greater than 2.0 mm; 2) sand, mean size between 0.0625 and 2.0 mm; and 3) mud, mean size less than 0.0625 mm. As shown in Figure 1-18, the general classes may be subdivided further.

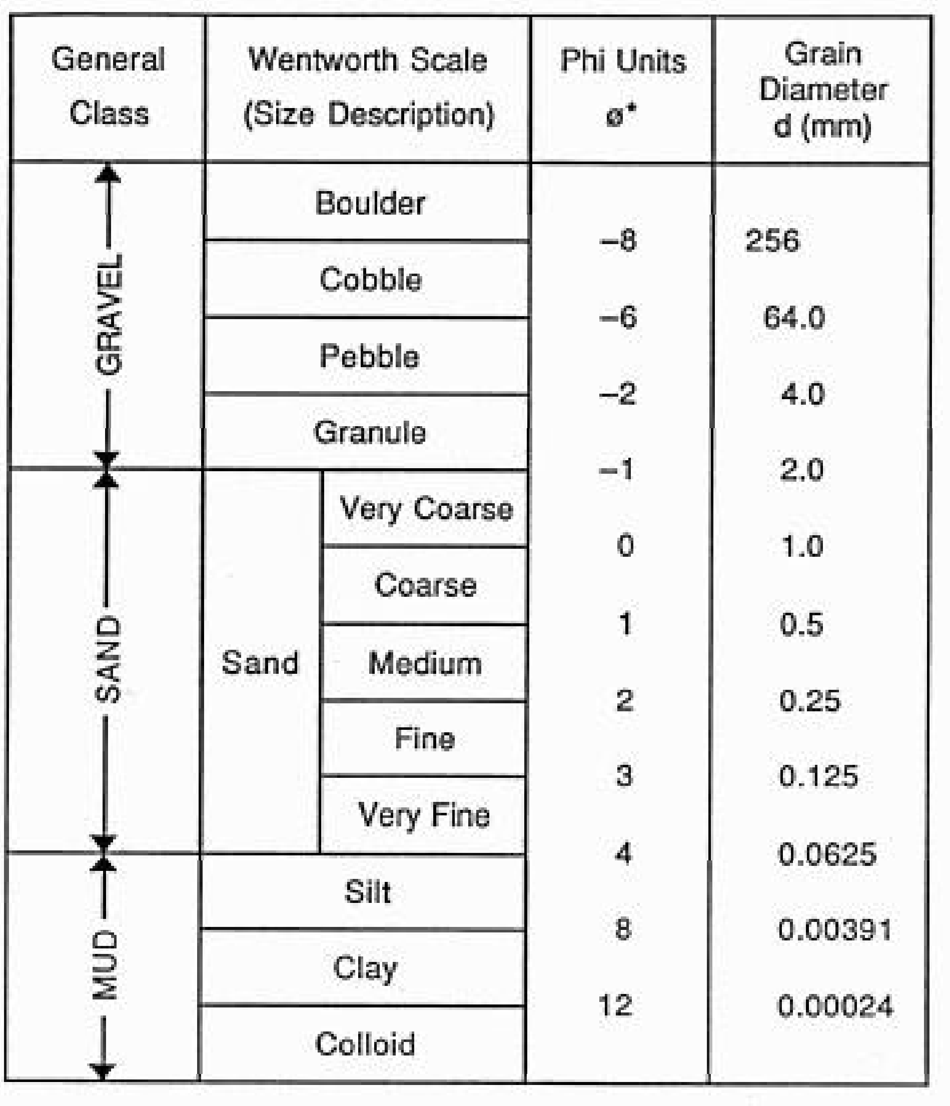
The Wentworth (1922) classification of grain size is the one used most widely by engineers and geologists. It is a logarithmic scale in that each class limit is twice as large as the next smaller class limit (Fig. 1-18). The property of having class limits so defined led Krumbein (1936) to propose a phi unit scale based on the following definition: phi units (F) = $-\log_2$ (diameter in mm). The phi scale of Krumbein, which is shown in Figure 1-18, is used to calculate statistical parameters of sediment grain-size populations.

The grain size of mud is measured by pipette analysis and that of sand with sieves or a settling tube. Gravel sizes are determined by measurements of the long, intermediate, and short axes of individual clasts. Ratios of the different clasts of gravel occurring on a beach (i.e., granule, pebble, cobble, boulder) can be estimated visually by comparing the beach sediment with the chart shown in Figure 3-14.

Composition of Beach Sediments

Sediments on beaches range from coarse-grained fragments of rocks, usually derived from local rock outcrops, to fine-grained sand, derived from 10's to hundreds of miles away. Quartz sand is the most common constituent of beach sediments because of its relative abundance in the earth's crust, as well as its chemical stability and resistance to abrasion. Carbonate sand beaches are common in tropical regions.

A summary of the generalized global occurrence of beach sediment, with regard to its composition, is given in Table 1-1.



General Class	Wentworth Scale (Size Description)		Phi Units ø*	Grain Diameter d (mm)
GRAVEL	Boulder			
			−8	256
	Cobble			
			−6	64.0
	Pebble			
			−2	4.0
	Granule			
			−1	2.0
SAND	Sand	Very Coarse		
			0	1.0
		Coarse		
			1	0.5
		Medium		
			2	0.25
		Fine		
			3	0.125
		Very Fine		
			4	0.0625
MUD	Silt			
			8	0.00391
	Clay			
			12	0.00024
	Colloid			

Figure 1-18. Grain-size scale. (From CERC, 1973; Fig. 4-7.) Phi unit scale is indicated by writing ø or phi after the numerical value.

Table 1-1. Generalized global occurrence of beach sediment.

Tropical regions	Carbonate sand composed of coral and algal fragments, shell, and carbonate precipitates abundant; quartz and rock fragments common in sand, especially in areas of eroding bedrock and near river mouths
Temperate regions	Quartz sand dominant; rock fragments and feldspar abundant in sand near river mouths and along coasts with eroding bedrock
Subpolar and polar regions	Gravel beaches of highly variable composition abundant; pure sand present on long, exposed beaches; quartz and rock fragments common in sand
Oceanic islands	Volcanic sands (normally black in color) and carbonate sands common

Estuaries—Bays—Lagoons

Introduction

Semi-enclosed water bodies of relatively small dimensions that separate the land from the sea are termed estuaries, bays, or lagoons, depending upon configuration and their hydrographic characteristics. On coastal plain shorelines, many of these water bodies are sheltered behind barrier islands. Drowned river valleys, such as Chesapeake Bay and Delaware Bay, are also common. The classic definition of the term "estuary" was given by Pritchard (1967) as follows:

> "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted by fresh water derived from land drainage".

Patterns of sedimentation in the "classic" estuaries are very complex, owing to the interaction of tidal currents, waves, and biogenic processes. Coarsest sediments occur in the inlets, on the tidal deltas, and in the larger tidal channels, whereas finest sediments occur on the tidal flats and in the salt marshes.

Relationship to Tidal Range

Hayes (1975) pointed out that the distribution of coastal habitats and sediments within semi-enclosed coastal water bodies is controlled largely by the tides. The coastal water bodies were grouped and discussed, as follows, into the three major tidal classes. General models for the three classes are given in Figure 1-19.

Microtidal Systems

The processes that dominate in microtidal systems are created by wind and wave effects. Wind tides are commonly generated and extensive wind-tidal flats may develop. The wave-formed features include aligned bay beaches, recurved spits, and cuspate spits. Tidal currents generated by the astronomical tide are important only at the inlet throat. In some instances, however, large intertidal shoals (flood-tidal deltas) can develop on the landward sides of the inlets.

Mesotidal Systems

These systems differ from those of microtidal areas in that sediments deposited by tidal currents begin to predominate. The barrier islands themselves are short and stubby, and the tidal deltas are large and conspicuous. Meandering tidal channels occur behind the barriers; point-bar deposits containing bedforms generated by tidal currents usually predominate in these channels. The principal sand deposits in mesotidal estuaries are the tidal deltas. Hayes (1969) proposed the following terminology for the two major sand deposits associated with tidal inlets: (a) ebb-tidal delta—sediment accumulation seaward of a tidal inlet, deposited primarily by ebb-tidal currents and modified by waves, and (b) flood-tidal delta—sediment accumulation formed on the landward side of an inlet by flood-tidal currents. The general morphological model for a tidal inlet is given in Figure 1-20.

Macrotidal Systems

The most prominent feature of this type of coastal water body is the overwhelming dominance of tidal currents. Such systems are usually broadmouthed and funnel-shaped. Sand deposition is normally concentrated in the center of the water body, away from shore, which is usually dominated by broad, muddy tidal flats. The sand bodies are long linear features oriented parallel with the tidal currents.

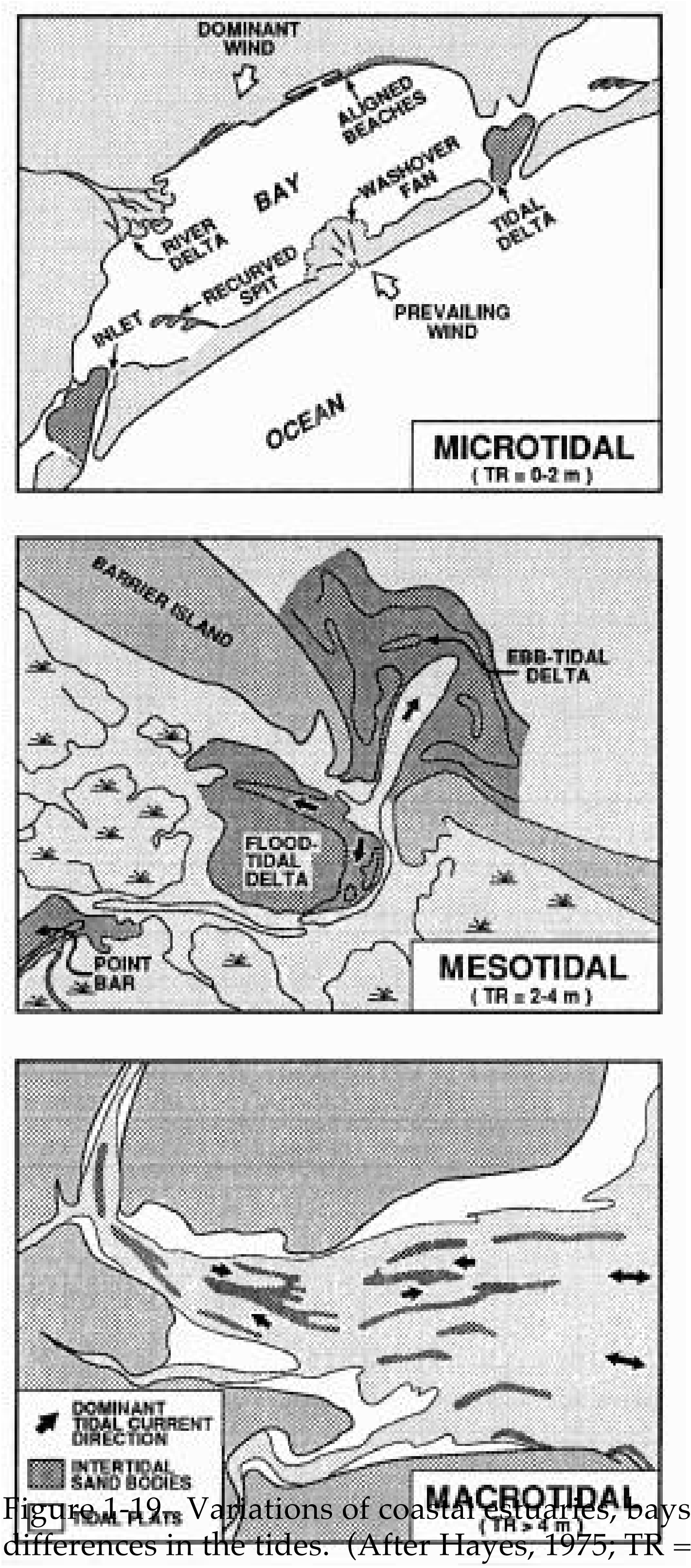


Figure 1-19. Variations of coastal estuaries, bays, and lagoons in response to differences in the tides. (After Hayes, 1975; TR = tidal range.)

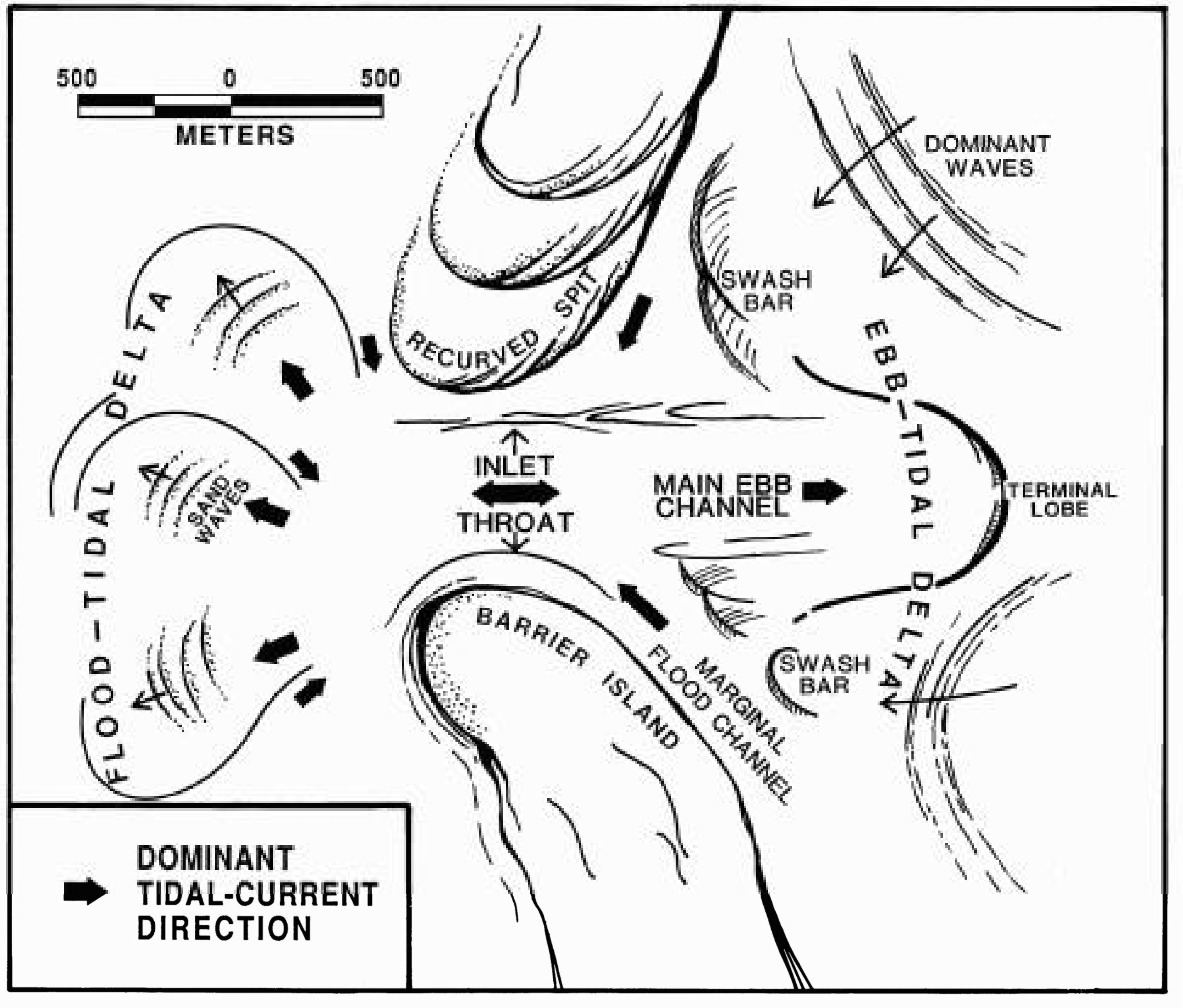


Figure 1-20. General model showing the morphological components of a tidal inlet.

Water Circulation and Mixing

As can be seen from the plan-view map of a group of Georgia estuaries (mesotidal) in Figure 1-21 and a hypothetical cross-section of a Chesapeake Bay-type estuary in Figure 1-22, oil spilled in either the entrance or the interior of a major estuary will be subjected to complex circulation and mixing patterns. Water circulation at the entrances to the Georgia estuaries is controlled by ebb- and flood-tidal currents, which are commonly both horizontally and vertically segregated, and complex wave-generated currents created by wave-refraction around the shoals at the estuary entrances (ebb-tidal deltas). The circulation pattern of both water masses and their suspended sediment loads inside major estuaries, which is illustrated in Figure 1-22, makes estuaries very effective traps for fine-grained, suspended sediments. The flocculation and entrapment of the sediments occurs predominantly in the zone of mixing between the fresh and salt water. This zone is sometimes referred to as the "turbidity maximum", because of the overabundance of suspended sediments in that zone. Oil from the *Amoco Cadiz* spill was entrapped in the bottom sediments of some of the estuaries in Brittany, France probably as a result of getting caught up in this type of circulation pattern.

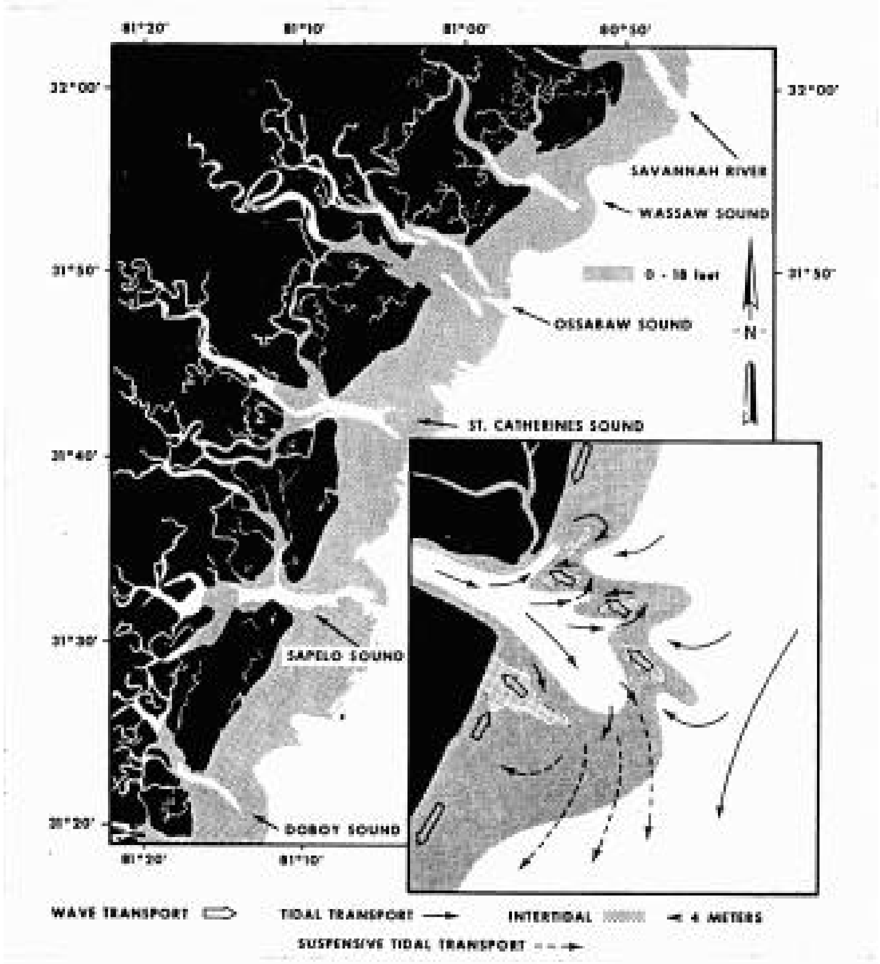


Figure 1-21. Water circulation and sedimentation patterns at the mouths of Georgia estuaries. (From Stanley and Swift, 1976; after Oertel, 1972.)

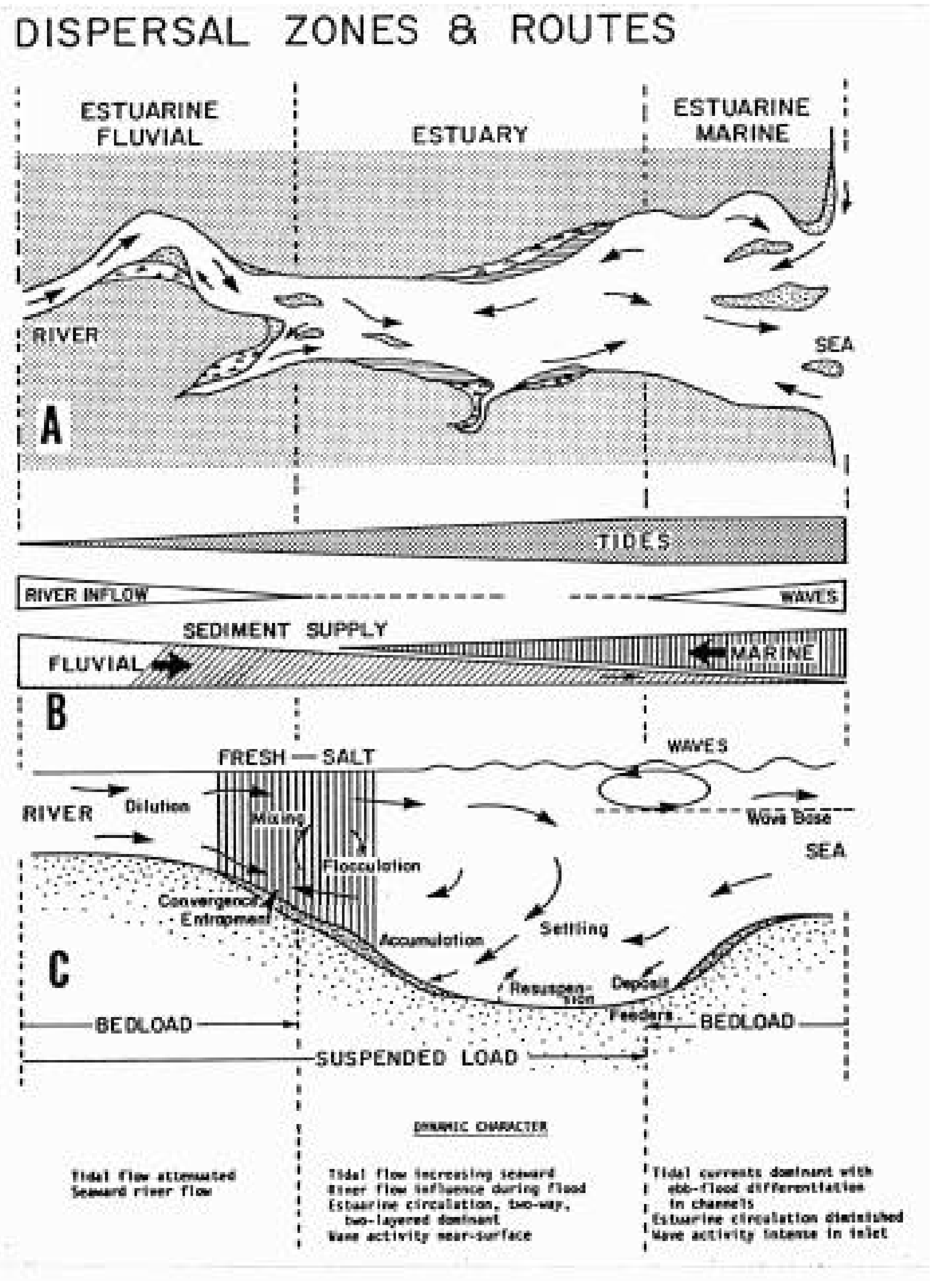


Figure 1-22. Conceptual model of sediment dispersal zones and circulation patterns in a hypothetical, Chesapeake Bay-type estuary. Note presence of zone of turbidity maximum and zone of suspended sediment entrapment in the area where salt and fresh waters mix (cross-section C). (From Nichols and Biggs, 1985; Fig. 2-48.)

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