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Fundamentals of Coastal Geology

PDH Credits:

3 PDH

Course No.:

OCG101

Publication Source:

US Corp of Engineers

"Coastal Terminology and Geologic Environments"

Chapter 2
Pub# EM 1110-2-1810

Release Date:
Jan. 1995

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Chapter 2
Coastal Terminology and Geologic Environments

2-1. General

Modern coastal environments are products of many complex interacting processes which are continually modifying rocks and sediments. Characterizing coastal geology is beset by difficulties in establishing precise and singular definitions of geologic features and processes. Sections 2-2 and 2-3 of this chapter describe the coastal zone and define broad terms such as "coast" and "shoreline." Section 2-4 discusses water level datums and tide terminology. The remainder of the chapter presents an overview of the geological, oceanographic, biological, and human factors that shape and modify landforms found along the shore. A better understanding of each factor is necessary in a systematic appraisal of the geology of a given project area.

2-2. Coastal Zone Definitions and Subdivisions

a. Introduction.

(1) Many coastal zone features and subdivisions are difficult to define because temporal variability or gradational changes between features obscure precise boundaries. In addition, nomenclature is not standardized, and various authors describe the same features using different names. If the same name is used, the intended boundaries may differ greatly. This ambiguity is especially evident in the terminology and zonation of shore and littoral areas. In the absence of a widely accepted standard nomenclature, coastal researchers would do well to accompany reports and publications with diagrams and definitions to ensure that readers will fully understand the authors' use of terms.

(2) The following subparagraphs present a suggested coastal zone definition and subdivision based largely, but not exclusively, on geological criteria. It does not necessarily coincide with other geological-based zonations or those established by other disciplines. It should be borne in mind that coastal zone geology varies greatly from place to place, and the zonations discussed below do not fit all regions of the world. For example, coral atolls are without a coast, shoreface, or continental shelf in the sense defined here. The Great Lakes and other inland water bodies have coasts and shorefaces but no continental shelves. Thus, while divisions and categories are helpful in describing coastal geology, flexibility and good descriptive text and illustrations are always necessary for adequate description of a given region or study site.

b. Coastal zone. In this manual, we suggest that *coastal zone* be defined as the transition zone where the land meets water, the region that is directly influenced by marine or lacustrine hydrodynamic processes. The coastal zone extends offshore to the continental shelf break and onshore to the first major change in topography above the reach of major storm waves. We exclude upland rivers from this discussion but do include river mouth deltas, where morphology and structure are a result of the dynamic interplay of marine and riverine forces. The coastal zone is divided into four subzones (Figure 2-1):

- Coast.
- Shore.
- Shoreface.
- Continental shelf.

c. Coast. The *coast* is a strip of land of indefinite width that extends from the coastline inland as far as the first major change in topography. Cliffs, frontal dunes, or a line of permanent vegetation usually mark this inland boundary. On barrier coasts, the distinctive back barrier lagoon/marsh/tidal creek complex is considered part of the coast. It is difficult to define the landward limit of the coast on large deltas like the Mississippi, but the area experiencing regular tidal exchange can serve as a practical limit (in this context, New Orleans would be considered "coastal"). The seaward boundary of the coast, the *coastline*, is the maximum reach of storm waves. Definition and identification of the coastline for mapping purposes are discussed in detail in Chapter 5, Section e. On shorelines with plunging cliffs, the coast and coastline are essentially one and the same. It is difficult to decide if a seawall constitutes a coast; the inland limit might better be defined at a natural topographic change.

d. Shore. The *shore* extends from the low-water line to the normal landward limit of storm wave effects, i.e., the coastline. Where beaches occur, the shore can be divided into two zones: *backshore* (or berm) and *foreshore* (or beach face). The foreshore extends from the low-water line to the limit of wave uprush at high tide. The backshore is horizontal while the foreshore slopes seaward. This distinctive change in slope, which marks the juncture of the foreshore and backshore, is called the

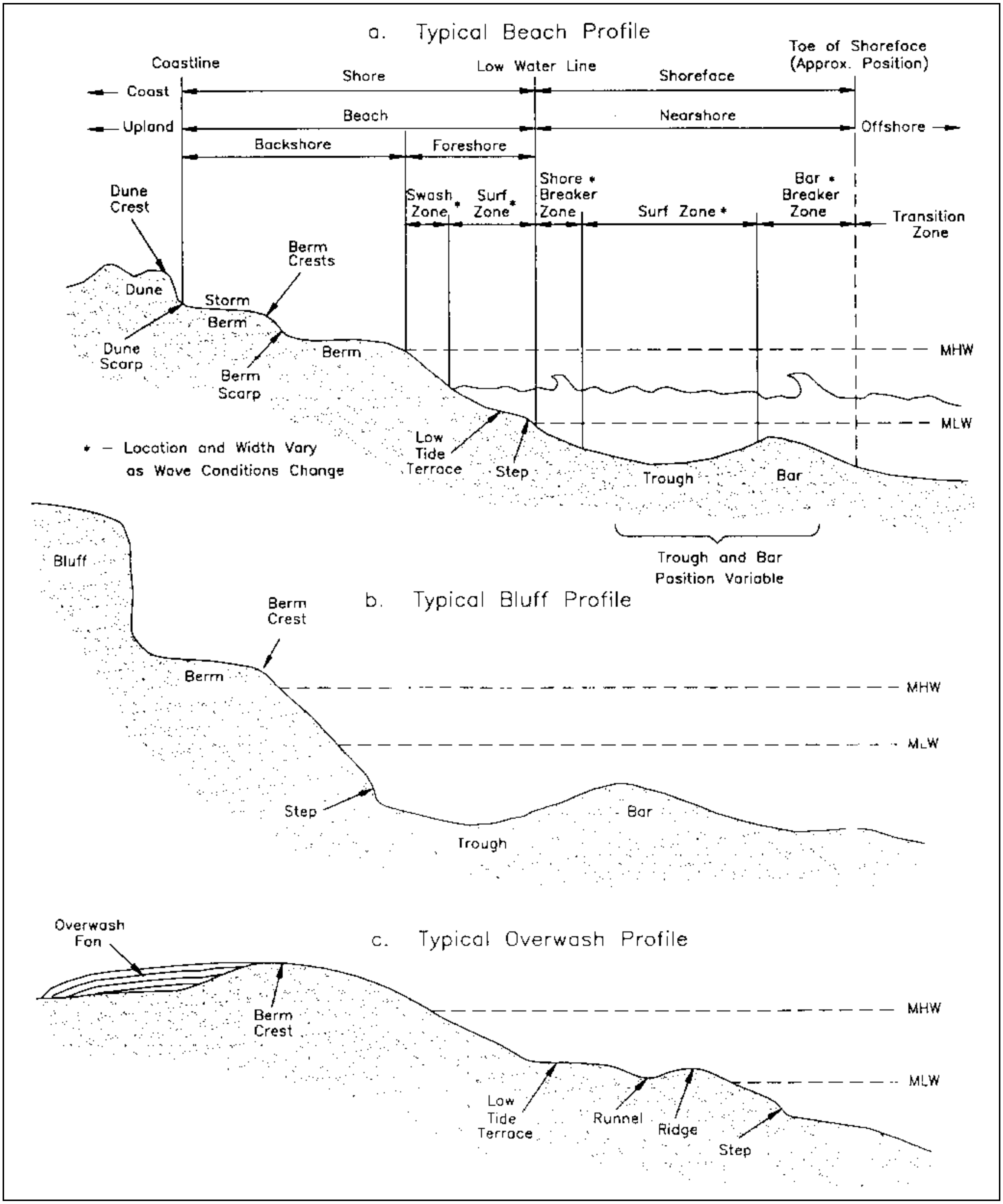

Figure 2-1. Definition of terms and features describing the coastal zone

beach or berm crest. A more detailed exposition of beach morphology and nomenclature is presented in Chapter 3.

e. Shoreface. The *shoreface* is the seaward-dipping zone that extends from the low-water line offshore to a gradual change to a flatter slope denoting the beginning of the continental shelf. The continental shelf transition is the *toe of the shoreface*. Its location can only be approximately marked due to the gradual slope change. Although the shoreface is a common feature, it is not found in all coastal zones, especially along low-energy coasts or those consisting of consolidated material. The shoreface can be delineated from survey profiles or from bathymetric charts such as the National Ocean Survey (NOS) 1:2000 series. The shoreface, especially the upper part, is the zone of most frequent and vigorous sediment transport.

f. Continental shelf. The *continental shelf* is the shallow seafloor that borders most continents (Figure 2-2). The shelf floor extends from the toe of the shoreface to the shelf break where the steeply inclined continental slope begins. It has been common practice to subdivide the shelf into inner-, mid-, and outer zones, although there are no regularly occurring geomorphic features on most shelves that suggest a basis for these subdivisions. Although the term *inner shelf* has been widely used, it is seldom qualified beyond arbitrary depth or distance boundaries. Site-specific shelf zonation can be based on project requirements and local geologic conditions. Some coastal areas (e.g., bays and the Great Lakes) do not extend out to a continental shelf.

2-3. Geologic Time and Definitions

a. Geologic fossil record. Geologists have subdivided geologic time into *eras*, *periods*, and *epochs* (Figure 2-3). Pioneering geologists of the 1800's based the zonations on the fossil record when they discovered that fossils in various rock formations appeared and disappeared at distinct horizons, thus providing a means of comparing and correlating the relative age of rock bodies from widely separated locations. For example, the boundary between the *Mesozoic* ("interval of middle life") and the *Cenozoic* ("interval of modern life") eras is marked by the disappearance of hundreds of species, including the dinosaurs, and the appearance or sudden proliferation of many new species (Stanley 1986). The fossil time scale was relative, meaning that geologists could compare rock units but could not assign absolute ages in years. It was not until the mid-20th century that scientists could measure the absolute age of units by radiometric dating. The geologic times listed in Figure 2-3, in millions of years, are best estimates based on radiometric dates.

b. Geologic time considerations for coastal engineering. The epochs of most concern to coastal engineers and geologists are the *Pleistocene* and *Recent* (also commonly

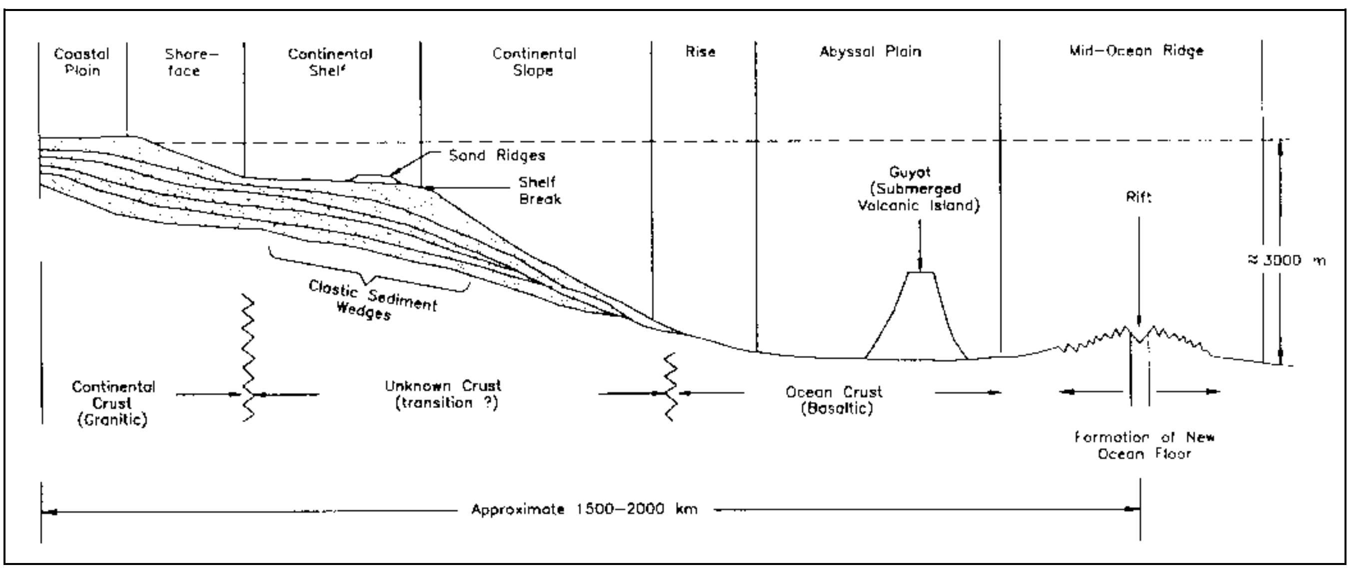

Figure 2-2. Continental shelf and ocean floor along a trailing-edge continent (i.e., representative of the U.S. Atlantic Ocean coast) (figure not to scale, great vertical exaggeration)

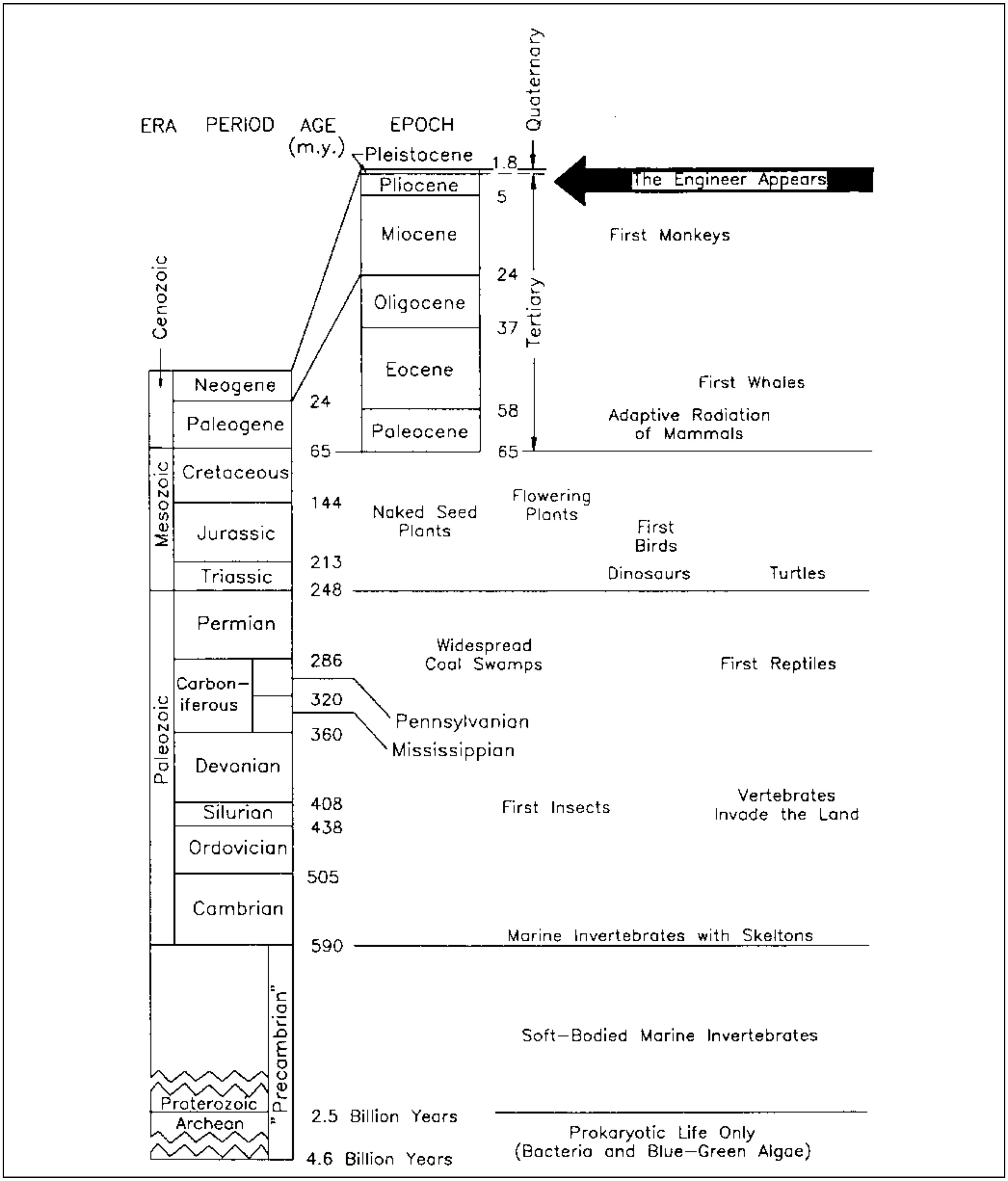

Figure 2-3. Geologic time scale. Chronological ages are based on radiometric dating methods (figure adapted from Stanley (1986))

known as the *Holocene*), extending back a total of 1.8 million years before present (my). *Quaternary* is often used to designate the period comprising the Pleistocene and Recent Epochs.

(1) The Pleistocene Epoch was marked by pronounced climatic fluctuations in the Northern Hemisphere - changes that marked the modern Ice Age. The continental glaciers that periodically covered vast areas of the northern continents during this time had profound influence on the surficial geology. Many geomorphic features in North America were shaped or deposited by the ice sheets (discussed in greater detail in Chapter 3). Flint's (1971) *Glacial and Quaternary Geology* is an exhaustive study of the effects of Pleistocene ice sheets on North American geology.

(2) The Holocene Transgression appears to have started around 15-18 thousand years ago with the beginning of global sea level rise. Presumably, a concurrent event was the waning of the continental glaciers possibly caused by warming climate around the world. Most of the dynamic, morphological features that we associate with the active coastal environment are Holocene in age, but the preexisting geology is often visible, as well. For example, the drumlins of Boston Harbor and the end moraine islands of southern New England (Long Island, Martha's Vineyard, and Block and Nantucket Islands) are deposits left by the Wisconsin stage glaciers (Woodsworth and Wigglesworth 1934), but barrier spits and beaches found along these shores are more recent (Holocene) features.

(3) North American glacial stages[1]. Worldwide climatic fluctuations and multiple glacial and interglacial stages were the overwhelming Quaternary processes that shaped the surficial geomorphology and biological diversity of our world. Major fluctuations in eustatic, or worldwide, sea level accompanied the waxing and waning of the continental glaciers. Oxygen isotope analysis of deep sea sediments suggests that there were as many as nine glacial and ten interglacial events in the last 700,000 years (Kraft and Chrzastowski 1985). North American stages and approximate ages are listed in Table 2-1. The most recent glacial stage was the Wisconsin in North America and the Würm in Europe, during which sea level was more than 100 m below present. In northern latitude coasts, the coastal worker will often encounter geologic and geomorphic evidence of the Wisconsin glacial stage. Less evidence remains of the earlier North American stages except raised shore terraces along parts of the U.S. Atlantic and Gulf coasts (e.g., see Winkler 1977; Winkler and Howard 1977).

2-4. Water Level Datums and Definitions

Critical in evaluating sea level information or in constructing shoreline change maps are the level and type of datum used. Because water levels are not constant over space and time, depths and elevations must be referenced from established datums. Tides are defined as the periodic rise and fall of water in coastal areas resulting from gravitational interactions of the earth, sun, and moon. *Water levels* are defined as the height, or stage, of water in lakes and reservoirs resulting from rainfall, snow melt, and other sources of drainage or seepage (EM 1110-2-1003).

a. Open coast (ocean) tidal datums. When elevations are referred to a tidal reference plane in coastal waters, *mean lower low water* (mllw) is normally used as the vertical datum (EM 1110-2-1003). For specific project requirements, other datums are sometimes used: *mean low water* (mlw), *mean sea level* (msl), *mean tide level* (mtl), *mean high water* (mhw), *mean higher high water* (mhhw) (Figure 2-4 and Table 2-2). To establish these datums, tide heights are collected and mean values computed by the NOS and related to a specific 19-year cycle known as the National Tidal Datum Epoch. Because of varying relative sea level in many areas, tidal datums are constantly changing and require continuous monitoring and updating. Some areas of the United States have established regional datums. These are based on combinations of other datums (e.g., *mean low gulf* (mlg) for the Gulf of Mexico), or on local measurements of water level over different periods. On project maps and documentation, all tidal datums must be clearly related to the fixed national survey datums (i.e., the National Geodetic Vertical Datum, 1929 adjustment (NGVD 29) or the North American Datum of 1983 (NAD 83)). Specific definitions of various datums and their relationship with geodetic datums are listed in Harris (1981), EM 1110-2-1414, and in references from the NOS.

[1] Stage is a time term for a major subdivision of a glacial epoch, including the glacial and interglacial events (Bates and Jackson 1984).

Table 2-1
North American Pleistocene Glacial and Interglacial Stages

Age (approx. years)[1]	Glacial and Interglacial Stages	Age (approx. years)[2]
12,000-Present	Recent (Holocene)	10,000-Present
150,000-12,000	Wisconsin	100,000-10,000
350,000-150,000	Sangamon Interglacial	300,000-100,000
550,000-350,000	Illinoisan	450,000-300,000
900,000-550,000	Yarmouth Interglacial	1,100,000-450,000
1,400,000-900,000	Kansan	1,300,000-1,100,000
1,750,000-1,400,000	Aftonian Interglacial	1,750,000-1,300,000
>2,000,000-1,750,000	Nebraskan	2,000,000-1,750,000
>2,000,000(?)	Older glaciations	

[1] Dates based on generalized curve of ocean-water temperatures interpreted from foraminifera in deep sea cores (curve reproduced in Strahler (1981))
[2] Dates from Young (1975) (original sources not listed)

b. Water level datums of the Great Lakes of North America (Lakes Superior, Huron, Michigan, Erie, and Ontario).

(1) Low water reference datums used on the Great Lakes and their connecting waterways are currently based on the International Great Lakes Datum (IGLD) 1985. This datum, established and revised by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, replaced IGLD 1955 in January 1992. The main differences between IGLD 1955 and IGLD 1985 are corrections in the elevations assigned to water levels (Table 2-3). This is a result of benchmark elevation changes due to adjustments for crustal movements, more accurate measurement of elevation differences, a new reference zero point location, and an expanded geodetic network. The reference zero point of IGLD 1985 is at Rimouski, Québec (Figure 2-5). The new 1985 datum establishes a set of elevations consistent for surveys taken within the time span 1982-1988. IGLD 1985 is referred to the North American Vertical Datum (NAVD) 1988. Note that the IGLD's are not parallel to NGVD 29 or NAVD 1988 because the Great Lakes datums are dynamic or geopotential heights that represent the hydraulic structure of the lakes and connecting waterways (EM 1110-2-1003).

(2) On the Great Lakes, astronomic tides have little influence on water levels. Instead, atmospheric pressure changes and winds cause most of the short-term water level fluctuations. Long-term changes are caused by regional hydrographic conditions such as precipitation, runoff, temperature and evapo-transpiration, snow melt, and ice cover (Great Lakes Commission 1986). Global climate variations, in turn, influence these factors. Crustal movements also influence levels. For example, the earth's crust at the eastern end of Lake Superior is rebounding about 25 cm/century faster than the western end, resulting in a drop of the datums (apparent higher water) at the west end at Duluth. Aquatic plant life and man-made control structures are additional factors that influence the exceedingly complex cycles of water level changes in the Great Lakes. As a result, the concept of mean water level is not applicable to these inland Great Lakes. Attempts to predict lake levels have not been entirely successful (Walton 1990).

2-5. Factors Influencing Coastal Geology

The coast is probably the most diverse and dynamic environment found anywhere on earth. Many geologic, physical, biologic, and anthropomorphic (human) factors are responsible for shaping the coast and keeping it in constant flux. Ancient geological events created, modified, and molded the rock and sediment bodies that form the foundation of the modern coastal zone. Over time, various physical processes have acted on this preexisting geology, subsequently eroding, shaping, and modifying the landscape. These processes can be divided into two broad classes: active forces, like waves and tides, which occur constantly, and long-term forces and global changes that affect the coast over time scales of years.

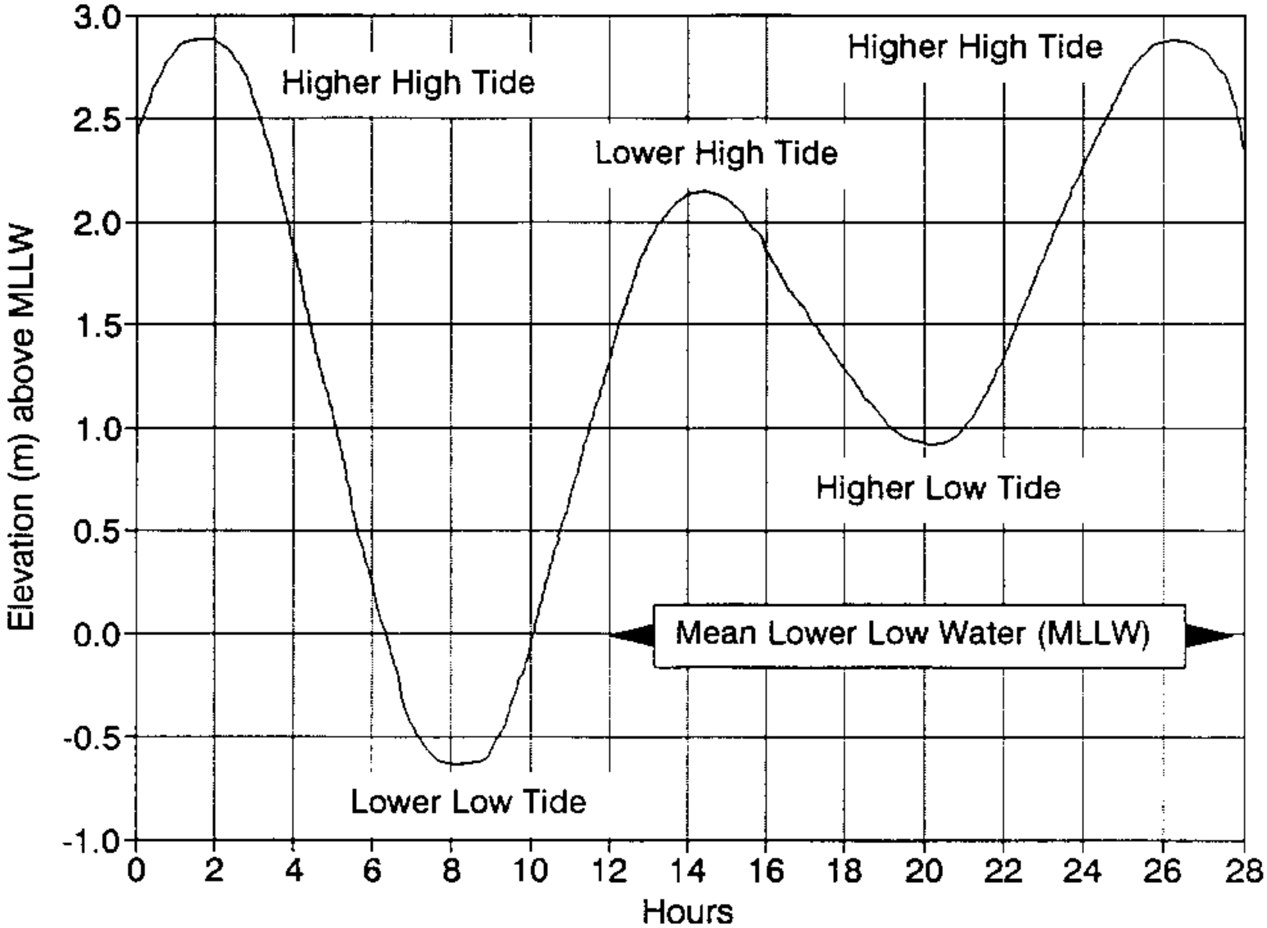

Figure 2-4. Tide curve for Yaquina Bay, Oregon (based on 6 years of observations). By definition, mean lower low water (mllw) is zero (from Oregon (1973))

a. Underlying geology and geomorphology.[1] The geologic setting of a coastal site controls surficial geomorphology, sediment type and availability, and overall gradient. The geology is modified by physical processes (e.g., waves and climate), biology, and man-made activities, but the overall "look" of the coast is primarily a function of the regional lithology and tectonics. These topics are discussed in the following paragraphs.

(1) Lithology. *Lithology* concerns the general character of rock or sediment deposits and is an important factor shaping the present coast. The most critical lithologic parameters responsible for a rock's susceptibility to erosion or dissolution are the mineral composition and the degree of consolidation. Striking contrasts often occur between coasts underlain by consolidated rock and those underlain by unconsolidated material. Marine processes are most effective when acting on uncemented material, which is readily sorted, redistributed, and sculpted into forms that are in a state of dynamic equilibrium with incident energy.

(a) Consolidated coasts. Consolidated rock consists of firm and coherent material. Coastal areas consisting of consolidated rock are typically found in hilly or mountainous terrain. Here, erosional processes are usually dominant. The degree of consolidation greatly influences the ability of a rocky coastline to resist weathering and erosion. Resistance depends on susceptibility to mechanical

[1] *Geomorphology* is a study of natural topographic features and patterns forming the earth's surface, including both terrestrial and subaqueous environments.

Table 2-2
Tidal Datums and Definitions, Yaquina Bay, Oregon[1]

Tide Staff (m)	Datum and Definition
4.42	**Extreme high tide.** The highest projected tide that can occur. It is the sum of the highest predicted tide and the highest recorded storm surge. Such an event would be expected to have a very long recurrence interval. In some locations, the effect of a rain-induced freshet must be considered. The extreme high tide level is used for the design of harbor structures.
3.85	**Highest measured tide.** The highest tide observed on the tide staff.
3.14	**Highest predicted tide.** Highest tide predicted by the Tide Tables.
2.55	**Mean higher high water.** The average height of the higher high tides observed over a specific interval. Intervals are related to the moon's many cycles, ranging from 28 days to 18.6 years. The time length chosen depends upon the refinement required. The datum plane of mhhw is used on National Ocean Survey charts to reference rocks awash and navigation clearances.
2.32	**Mean high water.** The average of all observed high tides. The average is of both the higher high and of the lower high tide recorded each day over a specific period. The datum of mhw is the boundary between upland and tideland. It is used on navigation charts to reference topographic features.
1.40	**Mean tide level.** Also called half-tide level. A level midway between mean high water and mean low water. The difference between mean tide level and local mean and sea level reflects the asymmetry between local high and low tides.
1.37	**Local mean sea level.** The average height of the water surface for all tide stages at a particular observation point. The level is usually determined from hourly height readings.
1.25	**Mean sea level.** A datum based upon observations taken over several years at various tide stations along the west coast of the United States and Canada. It is officially known as the Sea Level Datum of 1929, 1947 adj. Msl is the reference for elevations on U.S. Geological Survey Quadrangles. The difference between msl and local msl reflects many factors ranging from the location of the tide staff within an estuary to global weather patterns.
0.47	**Mean low water.** Average of all observed low tides. The average is of both the lower low and of the higher low tides recorded each day over a specific period. The mlw datum is the boundary line between tideland and submerged land.
0.00	**Mean lower low water.** Average height of the lower low tides observed over a specific interval. The datum plane is used on Pacific coast nautical charts to reference soundings.
-.88	**Lowest predicted tide.** The lowest tide predicted by the Tide Tables.
-.96	**Lowest measured tide.** Lowest tide actually observed on the tide staff.
-1.07	**Extreme low tide.** The lowest estimated tide that can occur. Used by navigation and harbor interests.

[1]Based on six years of observations at Oregon State University marine science center dock.

(From Oregon (1973))

and chemical weathering, hardness and solubility of constituent minerals and cementation, nature and density of voids, and climatic conditions. Rock type, bedding, jointing, and orientation of the strata greatly influence the geomorphic variability of the shoreline (Figure 2-6). For example, large portions of the shorelines of Lakes Superior, Huron, and Ontario are rocky and prominently display the structure of the underlying geology.

• *Mechanical weathering* is the disintegration of rock without alteration of its chemical nature. Examples of mechanical weathering include fluctuations in temperature (causing repetitive thermal expansion and contraction), expansion due to crystallization from salt or ice, wetting and drying, overburden fluctuations, and biological activity.

• *Chemical weathering* is the decomposition of rock material by changes in its chemical composition. Examples of this process include hydration and hydrolysis, oxidation and reduction, solution and carbonation, chelation, and biochemical reactions.

(b) Unconsolidated coasts. In contrast to consolidated coasts, depositional and erosional processes dominate unconsolidated coasts, which are normally found on low relief coastal plains or river deltas. Commonly,

Table 2-3
Low Water (chart) Datum for IGLD 1955 and IGLD 1985

	Low Water Datum in Meters	
Location	**IGLD 1955**	**IGLD 1985**
Lake Superior	182.9	183.2
Lake Michigan	175.8	176.0
Lake Huron	175.8	176.0
Lake St. Clair	174.2	174.4
Lake Erie	173.3	173.5
Lake Ontario	74.0	74.2
Lake St. Lawrence at Long Sault Dam, Ontario	72.4	72.5
Lake St. Francis at Summerstown, Ontario	46.1	46.2
Lake St. Louis at Pointe Claire, Québec	20.3	20.4
Montréal Harbour at Jetty Number 1	5.5	5.6

(From Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1992))

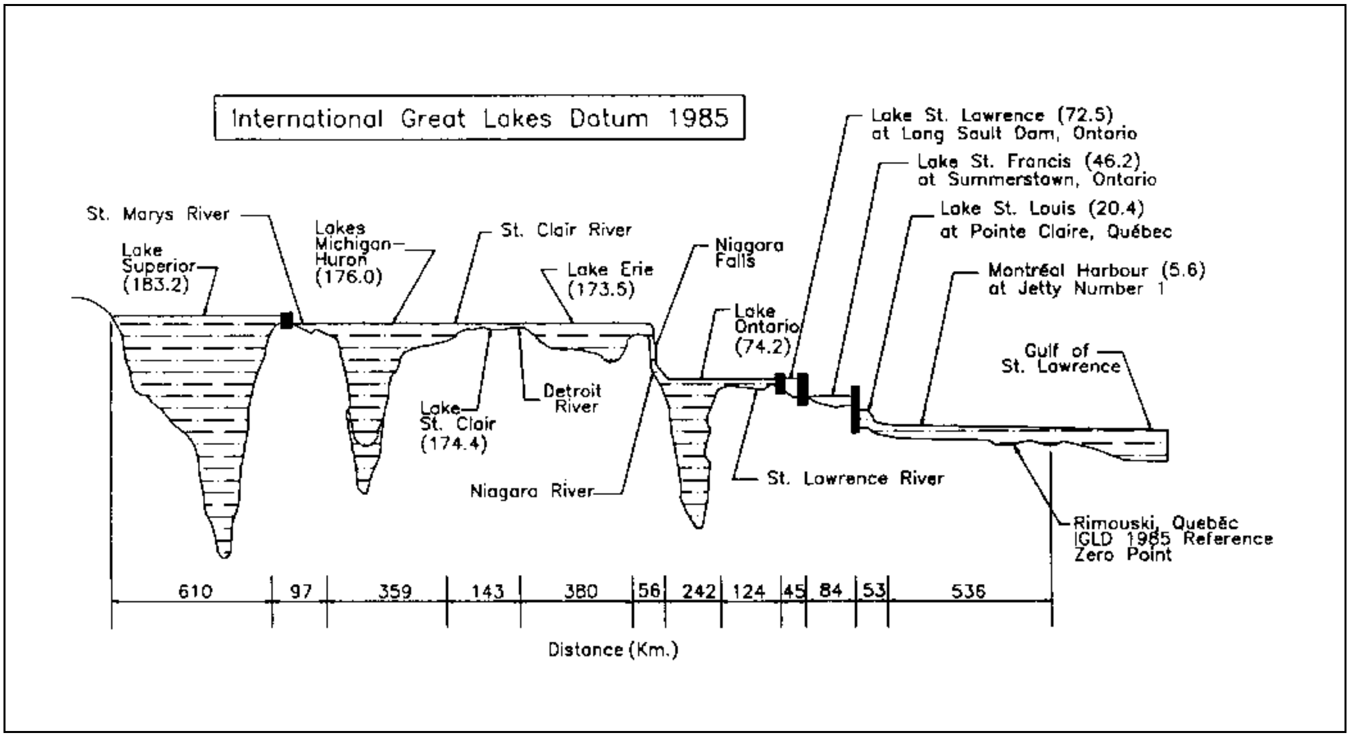

Figure 2-5. The reference zero point for IGLD 1985 at Rimouski, Quebec is shown in its vertical and horizontal relationship to the Great Lakes-St. Lawrence River System. Low water datums for the lakes in meters (from Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1992))

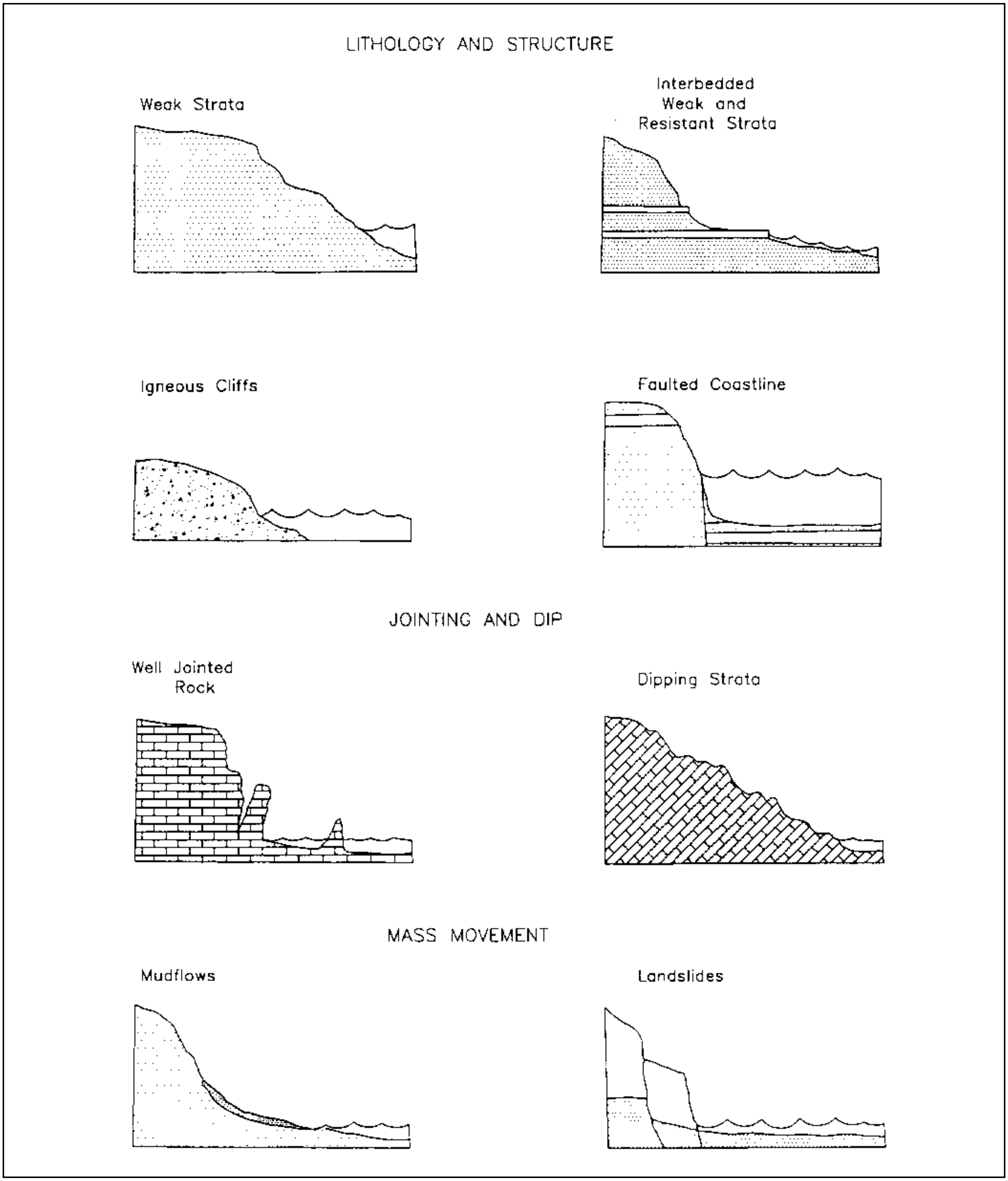

Figure 2-6. Cross-section views of aspects of geomorphic variability attributable to lithology, structure, and mass movement along semi-consolidated and consolidated coasts (from Mossa, Meisberger, and Morang 1992)

shorelines have been smoothed by erosion of protruding headlands and by the deposition of barrier islands, spits, and bay mouth barriers. Along unconsolidated coasts, large amounts of sediment are usually available, and morphological changes occur rapidly. Waves and currents readily alter relict geomorphic features in this environment. Figure 2-7 illustrates features associated with unconsolidated depositional environments. The Atlantic and Gulf of Mexico coasts of the United States are mostly unconsolidated, depositional environments (except select locations like the rocky shores in New England).

(2) Tectonics. Forces within the earth's crust and mantle deform, destroy, and create crustal material. These tectonic activities produce structural features such as faults and folds (anticlines and synclines) (Figure 2-8). Tectonic movements produce large-scale uplift and subsidence of land masses. The west coast of the United States is an example of a tectonically dominated coast, in sharp contrast to the east coast, which is mostly depositional. According to Shepard's (1973) coastal classification, a fault coast is characterized by a steep land slope that continues beneath the sea surface. The most prominent feature exhibited by a fault coast is a scarp where normal faulting has recently occurred, dropping a crustal block so that it is completely submerged and leaving a higher block standing above sea level (Figure 2-9). Examples of fault-block coasts are found in California. Active faults such as the Inglewood-Rose Canyon structural zone outline the coast between Newport Bay and San Diego, and raised terraces backed by fossil cliffs attest to continuing tectonism (Orme 1985).

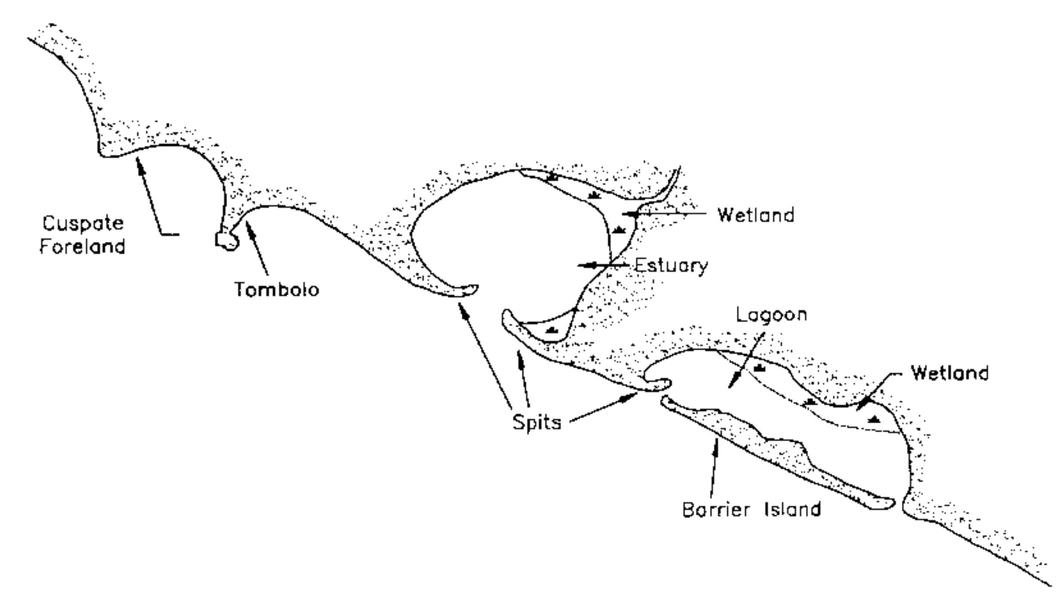

Figure 2-7. Examples of features associated with depositional coastal environments. These features consist mostly of unconsolidated sediments (after Komar (1976))

(3) Volcanic coasts. The eruption of lava and the growth of volcanoes may result in large masses of new crustal material. Conversely, volcanic explosions or collapses of existing volcanic cones can leave huge voids in the earth's surface known as calderas. When calderas and cones occur in coastal areas, the result is a coastline dominated by circular convex and concave contours (Shepard 1973). Coastlines of this sort are common on volcanic islands such as the Aleutians (Figure 2-10). The morphology of volcanic shores is discussed in more detail in Chapter 3.

b. High-frequency dynamic processes. The following paragraphs discuss processes that impart energy to the coastal zone on a continuous or, as with storms, repetitive basis. Any geological or engineering investigation of the coastal zone must consider the sources of energy that cause erosion, move sediment, deposit sediment, and result in the rearrangement of the preexisting topography. These processes also result in temporary changes in water levels along the coast. Long-term sea level changes are discussed in paragraph 2-6.

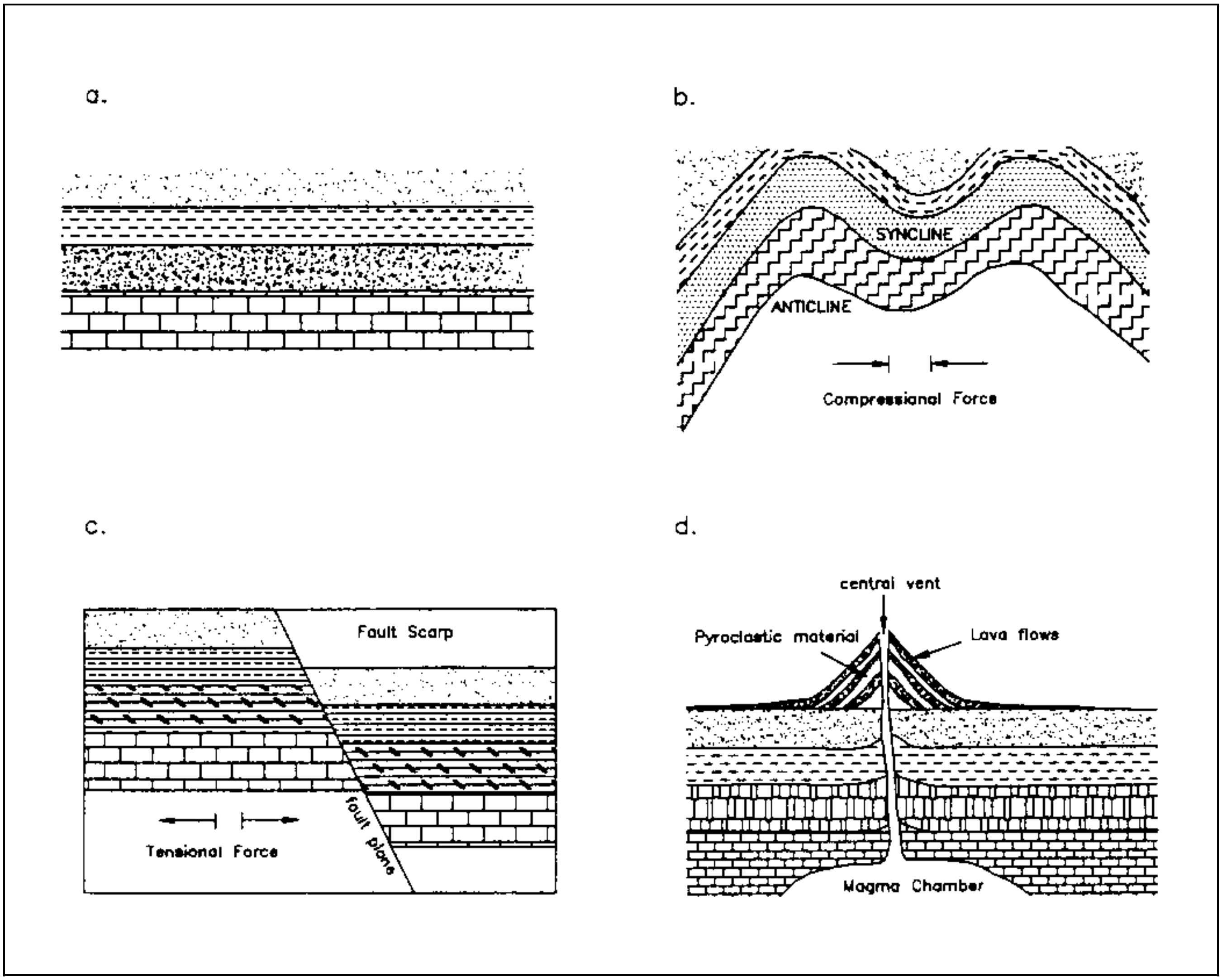

Figure 2-8. Examples of tectonically produced features: (a) stable undeformed block; (b) symmetrical folding resulting from compressional forces; (c) normal faulting resulting from tensional forces; (d) composite volcano composed of alternating layers of pyroclastic material (ash) and lava flows

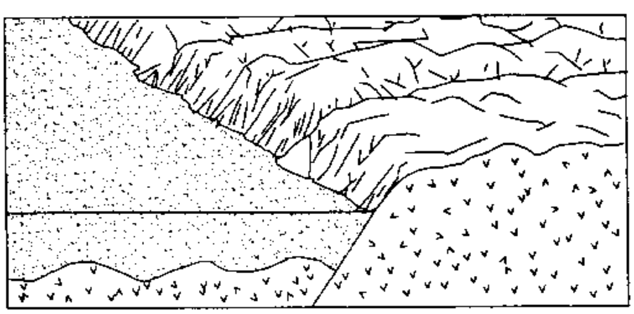

Figure 2-9. Example of a fault coast exhibiting a prominent fault scarp

Figure 2-10. Example of a volcanic coast

(1) Waves.

(a) Water waves (sometimes called *gravity waves*) are the dominant force driving littoral processes on open coasts. The following quotes from the *Shore Protection Manual* (1984) underscore the significance of waves in the coastal zone:

> Waves are the major factor in determining the geometry and composition of beaches and significantly influence the planning and design of harbors, waterways, shore protection measures, coastal structures, and other coastal works. Surface waves generally derive their energy from the winds. A significant amount of this wave energy is finally dissipated in the nearshore region and on the beaches.
>
> Waves provide an important energy source for forming beaches; sorting bottom sediments on the shoreface; transporting bottom materials onshore, offshore, and alongshore; and for causing many of the forces to which coastal structures are subjected. An adequate understanding of the fundamental physical processes in surface wave generation and propagation must precede any attempt to understand complex water motion in the nearshore areas of large bodies of water. Consequently, an understanding of the mechanics of wave motion is essential in the planning and design of coastal works.

(b) Energy in the nearshore zone occurs over a broad band of frequencies, of which gravity waves occupy the range from about 1 to 30 sec (Figure 2-11). Waves with a period shorter than 5 or 6 sec, known as seas, are usually generated by local winds; waves that have traveled out of their generating area are known as *swell*. Swell waves are more regular, and longer period and have flatter crests than local waves. Waves create currents, which move sediment both onshore and offshore as well as parallel to the coast by means of longshore currents.

(c) Wave climate generally changes seasonally, thus resulting in regular adjustment of the beach profile. Along California and other areas, the more severe wave climate of winter causes erosion of the shore. The eroded material is usually transported to the upper shoreface, where it forms submarine bars. With the return of milder conditions in the summer months, the sand usually returns to the beach (Bascom 1964).

(d) Because of space limitations, a comprehensive discussion of waves is not possible in this manual. Bascom's (1964) *Waves and Beaches* is a readable general introduction to the subject. A concise overview of water wave mechanics is presented in EM 1110-2-1502; more detailed treatments are in Kinsman (1965), Horikawa (1988), and Le Méhauté (1976). Interpreting and applying wave and water level data are covered in EM 1110-2-1414. Quality control issues for users of wave data are discussed in Chapter 5 of this manual.

(2) Tides.

(a) The most familiar sea level changes are those produced by astronomical tides. *Tides* are a periodic rise and fall of water level caused by the gravitational interaction among the earth, moon, and sun. Because the earth is not covered by a uniform body of water, tidal ranges and periods vary from place to place and are dependent upon the natural period of oscillation for each water basin (Komar 1976). Tidal periods are characterized as diurnal (one high and one low per day), semidiurnal (two highs and two lows per day), and mixed (two highs and two lows with unequal heights) (Figure 2-12). In the coastal zone, variations in topography, depth, seafloor sediment type, and lateral boundaries also affect the tide. Tide heights can be predicted from the astronomic harmonic components. The National Ocean Survey (NOS) prints annual tide tables for the Western Hemisphere (see Appendix F for addresses of Federal agencies). Background information and theory are presented in physical oceanography textbooks (e.g., von Arx 1962; Knauss 1978). Dronkers (1964) and Godin (1972) are advanced texts on tidal analysis.

(b) The importance of tides to coastal geological processes is threefold. First, the periodic change in water level results in different parts of the foreshore being exposed to wave energy throughout the day. In regions with large tidal ranges, the water may rise and fall 10 m, and the shoreline may move laterally several kilometers between high and low water. This phenomenon is very important biologically because the ecology of tidal flats depends on their being alternately flooded and exposed. The geological significance is that various parts of the intertidal zone are exposed to erosion and deposition.

(c) Second, tidal currents themselves can erode and transport sediment. Generally, tidal currents become stronger near the coast and play an increasingly important role in local circulation (Knauss 1978). Because of the rotating nature of the tidal wave in many locations (especially inland seas and enclosed basins), ebb and flood currents follow different paths. As a result, residual motions can be highly important in terms of transport and

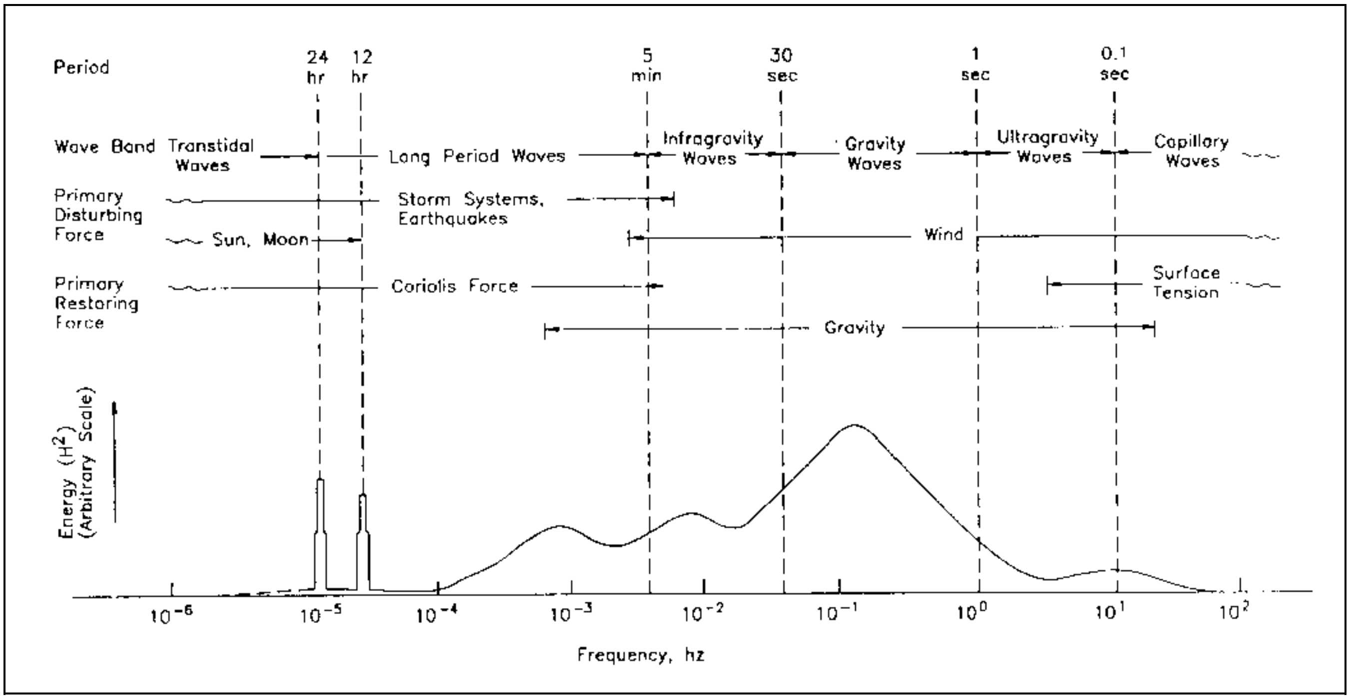

Figure 2-11. Distribution of ocean surface wave energy (after Kinsman (1965))

sedimentation (Carter 1988). In inlets and estuaries, spatially asymmetric patterns of ebb and flood may cause mass transport of both water and sediment.

(d) Third, tides cause the draining and filling of tidal bays. These bays are found even in low-tide coasts such as the Gulf of Mexico. This process is important because it is related to the cutting and migration of tidal inlets and the formation of flood- and ebb-tidal shoals in barrier coasts. The exchange of seawater in and out of tidal bays is essential to the life cycle of many marine species.

(3) Energy-based classification of shorelines.

(a) Davies (1964) applied an energy-based classification to coastal morphology by subdividing the world's shores according to tide range. Hayes (1979) expanded this classification, defining five tidal categories for coastlines:

- Microtidal, < 1 m.
- Low-mesotidal, 1-2 m.
- High-mesotidal, 2-3.5 m.
- Low-macrotidal, 3.5-5 m.
- Macrotidal, > 5 m.

The Hayes (1979) classification was based primarily on shores with low to moderate wave power and was intended to be applied to trailing edge, depositional coasts.

(b) In the attempt to incorporate wave energy as a significant factor modifying shoreline morphology, five shoreline categories were identified based on the relative influence of tide range versus mean wave height (Figure 2-13) (Nummedal and Fischer 1978; Hayes 1979; Davis and Hayes 1984):

- Tide-dominated (high).
- Tide-dominated (low).
- Mixed-energy (tide-dominated).
- Mixed energy (wave-dominated).
- Wave-dominated.

(c) The approximate limit of barrier island development is in the field labeled "mixed energy

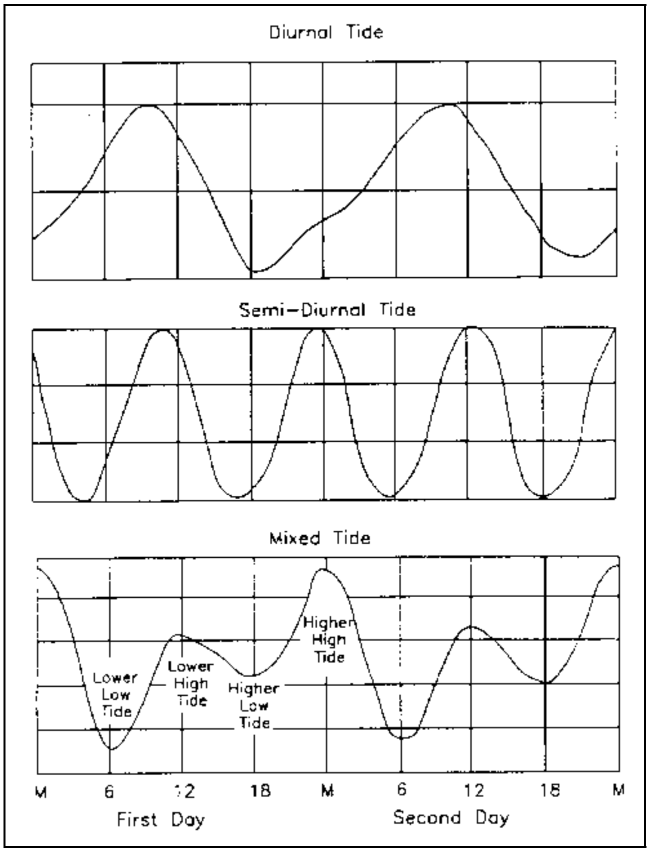

Figure 2-12. Examples of the diurnal, semidiurnal, and mixed tides

(tide-dominated)." Notice that these fields cover a range of tide and wave heights. It is the relative effects of these processes that are important, not the absolute values. Also, at the lower end of the energy scales, there is a delicate balance between the forces; tide-dominated, wave-dominated, or mixed-energy morphologies may develop with very little difference in wave or tide parameters. By extension, tidal inlets have sometimes been classified using this nomenclature.

(d) Continuing research has shown, however, that earlier approaches to classifying the coast on the basis of tidal and wave characteristics have been oversimplified because many other factors can play critical roles in determining shoreline morphology and inlet characteristics (Davis and Hayes 1984; Nummedal and Fischer 1978). Among these factors are:

- Physiographic setting and geology.
- Tidal prism.
- Sediment availability.
- Influence of riverine input.
- Bathymetry of the back-barrier bays.
- Meteorology and the influence of storm fronts.

(4) Meteorology. *Meteorology* is the study of the spatial and temporal behavior of atmospheric phenomena. *Climate* characterizes the long-term meteorologic conditions of an area, using averages and various statistics. Factors directly associated with climate such as wind, temperature, precipitation, evaporation, chemical weathering, and seawater properties all affect coastal geology. The shore is also affected by wave patterns that may be due to local winds or may have been generated by storms thousands of kilometers away. Fox and Davis (1976) is an introduction to weather patterns and coastal processes. Detailed analyses of wind fields and wave climatology have been conducted by the USACE Wave Information Studies (WIS) program (Appendix D). Hsu (1988) reviews coastal meteorology fundamentals.

(a) Wind. Wind is caused by pressure gradients, horizontal differences in pressure across an area. Wind patterns range in scale from global, which are generally persistent, to local and short duration, such as thunderstorms.

(b) Direct influence of wind. Wind has a great influence on coastline geomorphology, both directly and indirectly. The direct influence includes wind as an agent of erosion and transportation. It affects the coastal zone by eroding, transporting, and subsequently depositing sediment. Bagnold (1954) found that a proportional relationship exists between wind speed and rate of sand movement. The primary method of sediment transport by wind is through saltation, or the bouncing of sediment grains across a surface. Two coastal geomorphic features that are a direct result of wind are dunes and related blowouts (Pethick 1984). *Dunes* are depositional features whose form and size are a result of sediment type, underlying topography, wind direction, duration, and strength. *Blowouts* form when wind erodes an unvegetated area, thus removing the sand and leaving a low depression. These features are discussed in more detail in Chapter 3.

(c) Indirect effect. Wind indirectly affects coastal geomorphology as wind stress upon a water body causes the formation of waves and oceanic circulation.

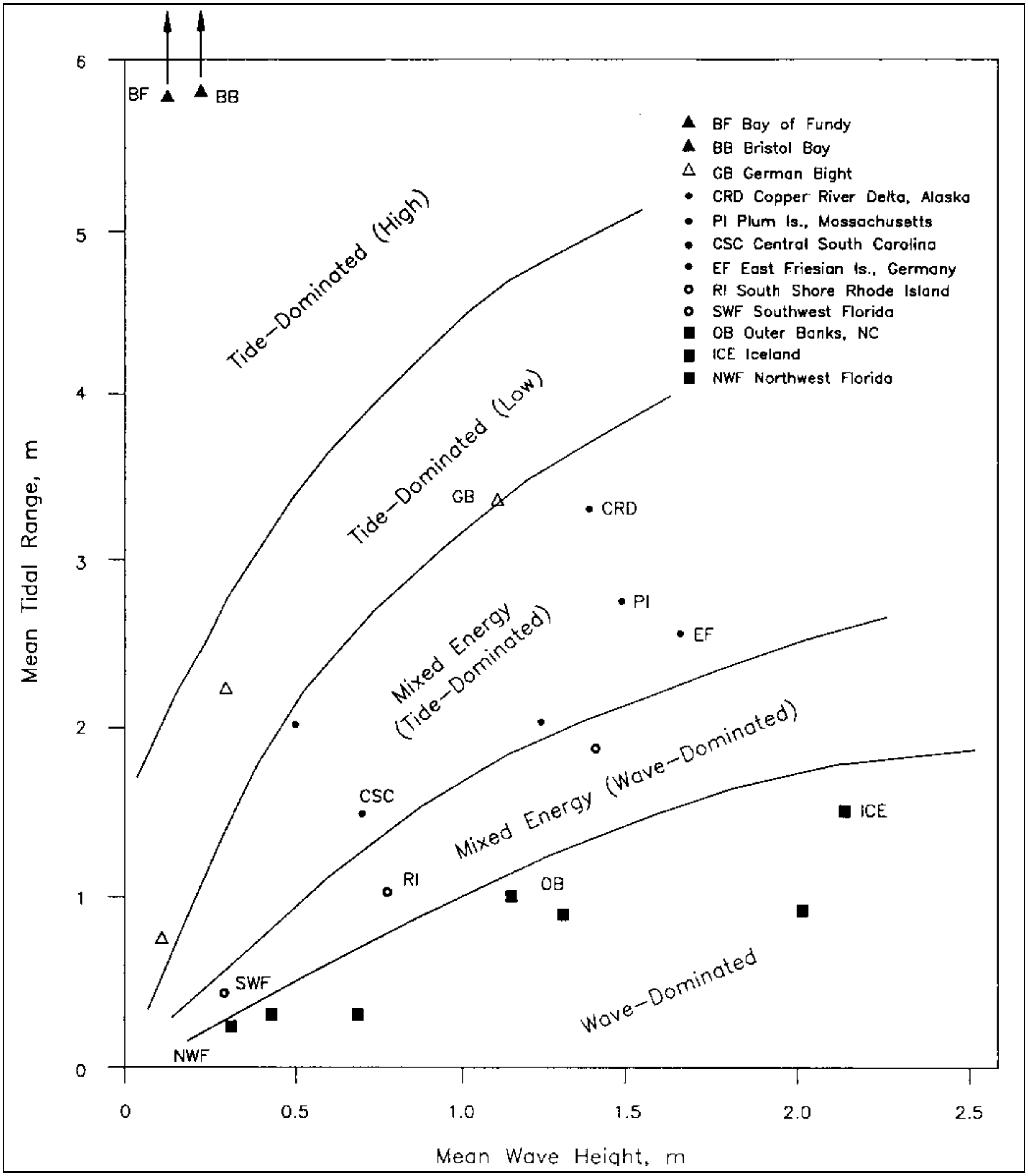

Figure 2-13. Energy-based classification of shorelines (from Hayes (1979))

(d) Land/sea breeze. Diurnal variations in the wind result from differential heating of the ocean and land surfaces. During the day, especially in summer, the heating of the land causes the air to expand and rise, thus forming an area of low pressure. The pressure gradient between the water and the land surfaces causes a landward-directed breeze. At night, the ocean cools less rapidly than does the land, thus resulting in air rising over the ocean and subsequently seaward-directed breezes. These breezes are rarely greater than 8 m/sec (15 knots) and therefore do not have a great effect upon coastline geomorphology, although there may be some offshore-onshore transport of sediment on beaches (Komar 1976).

(e) Water level setup and setdown. Onshore winds cause a landward movement of the surface layers of the water and thus a seaward movement of deeper waters. Strong onshore winds, if sustained, may also cause increased water levels or setup. The opposite occurs during offshore winds.

(f) Seiches. *Seiches* are phenomena of standing oscillation that occur in large lakes, estuaries, and small seas in response to sudden changes in barometric pressure, violent storms, and tides. This condition causes the water within the basin to oscillate much like water sloshing in a bowl.

(5) Tropical storms. A *cyclone* is a system of winds that rotates about a center of low atmospheric pressure clockwise in the Southern Hemisphere and anti-clockwise in the Northern Hemisphere (Gove 1986). *Tropical storm* is a general term for a low-pressure, synoptic-scale[1] cyclone that originates in a tropical area. At maturity, tropical cyclones are the most intense and feared storms in the world; winds exceeding 90 m/sec (175 knots or 200 mph) have been measured, accompanied by torrential rain (Huschke 1959). By convention, once winds exceed 33 m/sec (74 mph), tropical storms are known as *hurricanes* in the Atlantic and eastern Pacific, *typhoons* in the western Pacific (Philippines and China Sea), and cyclones in the Indian Ocean.

(a) Tropical storms can cause severe beach erosion and destruction of shore-front property because elevated sea level, high wind, and depressed atmospheric pressure can extend over hundreds of kilometers. Tropical storms can produce awesome property damage (Table 2-4) and move vast quantities of sediment. The great Gulf of Mexico hurricane of 1900 inundated Galveston Island, killing 6,000 residents (NOAA 1977). The hurricane that devastated Long Island and New England in September of 1938 killed 600 people and eliminated beach-front communities along the southern Rhode Island shore (Minsinger 1988). Survivors reported 50-ft breakers sweeping over the Rhode Island barriers (Allen 1976). Hurricane Hugo hit the U.S. mainland near Charleston, SC, on September 21, 1989, causing over $4 billion in damage, eroding the barriers, and producing other geologic changes up to 180 km north and 50 km south of Charleston (Davidson, Dean, and Edge 1990; Finkl and Pilkey 1991). Simpson and Riehl (1981) have examined the effects of hurricanes in the United States. This work and Neumann et al. (1987) list landfall probabilities for the United States coastline. Tropical storms from 1871 to 1986 are plotted in Neumann et al. (1987). Tannehill (1956) identified all known Western Hemisphere hurricanes before the 1950's. Representative tropical storm tracks are shown in Figure 2-14.

(b) The Saffir-Simpson Scale has been used for over 20 years by the U.S. National Weather Service to compare the intensity of tropical cyclones (Table 2-5). Cyclones are ranked into five categories based on maximum wind speed.

(c) During tropical storms and other weather disturbances, water level changes are caused by two factors:

• *Barometric pressure.* Barometric pressure has an inverse relationship to sea level. As atmospheric pressure increases, the sea surface is depressed so that the net pressure on the seafloor remains constant. Inversely, as atmospheric pressure decreases, surface water rises. The magnitude of the "inverse barometer effect" is about 0.01 m for every millibar of difference in pressure, and in areas affected by tropical storms or hurricanes, the potential barometric surge may be as high as 1.5 m (Carter 1988).

• *Storm surges.* In shallow water, winds can pile up water against the shore or drive it offshore. Storm surges, caused by a combination of low barometric pressure and high onshore winds, can raise sea level several meters, flooding coastal property. The Federal Emergency Management Agency (FEMA) determines base flood elevations for the coastal counties of the United States. These elevations include still-water-level flood surges that have a 100-year return interval. In light of rising sea level along most of the United States, it seems prudent that Flood Insurance Rate Maps be periodically adjusted (National Research Council 1987). Besides wind forcing,

[1] Synoptic-scale refers to large-scale weather systems as distinguished from local patterns such as thunderstorms.

Table 2-4
Biggest Payouts by Insurance Companies for U.S. Catastrophes

Date	Event (Region of Greatest Influence)	Insured loss (millions)[1]
Aug. 1992	Hurricane Andrew (Florida, Louisiana)[2]	$16,500
Sep. 1989	Hurricane Hugo (S. Carolina)	4,195
March 1993	Winter storms (24 states; coastal California)	1,750
Oct. 1991	Oakland, CA, fire	1,700
Sep. 1992	Hurricane Iniki (Hawaiian Is.)	1,600
Oct. 1989	Loma Prieta, CA, earthquake	960
Dec. 1983	Winter storms, 41 states	880
April-May 1992	Los Angeles riots	775
April 1992	Wind, hail, tornadoes, floods (Texas and Oklahoma)	760
Sep. 1979	Hurricane Frederic (Mississippi, Alabama)	753
Sep. 1938	Great New England Hurricane (Long Island, Rhode Island, Connecticut, Massachusetts)	400[3]

Notes:
1. Total damage costs exceed insurance values because municipal structures like roads are not insured.
2. Andrew caused vast property damage in south central Florida, proving that hurricanes are not merely coastal hazards.
3. Multiplying the 1938 damage value by 4 or 5 gives a crude estimate in 1990's Dollars (Data source: Minsinger 1988).

(Source: *The New York Times,* December 28, 1993, citing insurance industry and State of Florida sources)

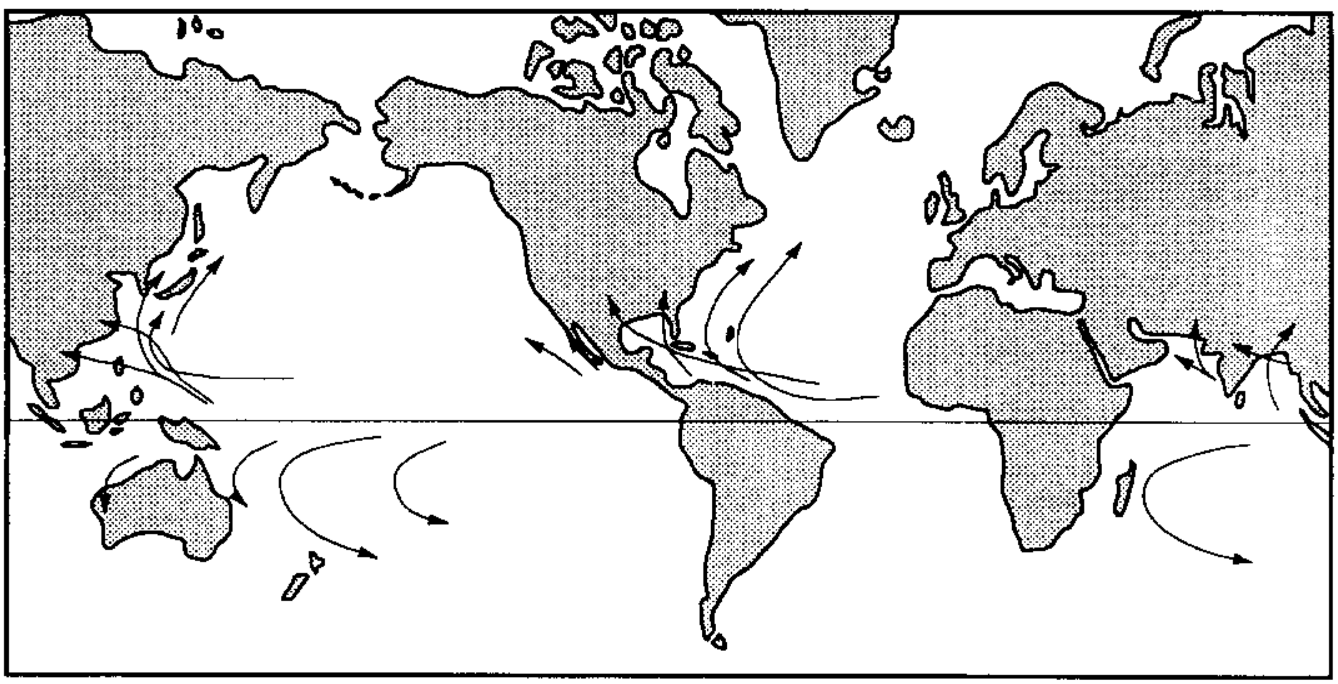

Figure 2-14. Worldwide tropical storm pathways (from Cole (1980))

Table 2-5
Saffir-Simpson Damage-Potential Scale

Scale Number (category)	Central pressure (millibars)	Wind speed (miles/hr)	Wind speed (m/sec)	Surge (ft)	Surge (m)	Damage
1	≥980	74-95	33-42	4-5	~1.5	Minimal
2	965-979	96-110	43-49	6-8	~2-2.5	Moderate
3	945-964	111-130	50-58	9-12	~2.6-3.9	Extensive
4	920-944	131-155	59-69	13-18	~4-5.5	Extreme
5	<920	>155	>69	>18	>5.5	Catastrophic

(From Hsu (1988); originally from Simpson and Riehl (1981))

ocean waves generated by storms can temporarily increase water levels tens of centimeters. Analysis procedures for predicting surge heights are detailed in EM 1110-2-1412.

(6) Extratropical storms. *Extratropical cyclones* (ET's) are cyclones associated with migratory fronts occurring in the middle and high latitudes (Hsu 1988). Although hurricanes are the most destructive storms to pass over the U.S. Atlantic coast, less powerful ET's, more commonly known as winter storms or "northeasters," have also damaged ships, eroded beaches, and taken lives. Northeasters are not as clearly defined as hurricanes and their wind speeds seldom approach hurricane strength. On the other hand, ET's usually cover broader areas than hurricanes and move more slowly; therefore, ET's can generate wave heights that exceed those produced by tropical storms (Dolan and Davis 1992).

(a) Most Atlantic northeasters occur from December through April. Dolan and Davis (1992) have tabulated historic ET's and calculated that the most severe ones are likely to strike the northeast coast in October and January.

(b) The *Halloween Storm* of October 1991 was one of the most destructive northeasters to ever strike the Atlantic coast. The system's lowest pressure dipped to 972 mb on October 30. Sustained winds about 40-60 knots persisted for 48 hr, generating immense seas and storm surges (Dolan and Davis 1992). Another famous northeaster was the *Ash Wednesday Storm* of 1962, which claimed 33 lives and caused great property damage.

(c) In early 1983, southern California was buffeted by the most severe storms in 100 years, which devastated coastal buildings and caused tremendous erosion. During one storm in January 1983, which coincided with a very high tide, the cliffs in San Diego County retreated as much as 5 m (Kuhn and Shepard 1984). Further north, the storm was more intense and cliff retreat of almost 30 m occurred in places. Kuhn and Shepard (1984) speculated that the unusual weather was linked to the eruption of El Chichon Volcano in the Yucatan Peninsula in March 1982. They noted that the 1983 storms in California were the most intense since the storms of 1884, which followed the August 27, 1883, explosion of Krakatoa.

(d) At this time, weather forecasters still have difficulty forecasting the development and severity of ET's. Coastal planners and engineers must anticipate that powerful storms may lash their project areas and need to apply conservative engineering and prudent development practices to limit death and property destruction.

c. Biological factors.

Coastal areas are normally the sites of intense biological activity. This is of enormous geological importance in some areas, while being insignificant and short-lived in others. Biological activity can be constructive; e.g., the growth of massive coral reefs, or it can be destructive, as when boring organisms help undermine sea cliffs. Remains from marine organisms having hard skeletal parts, usually composed of calcium carbonate, contribute to the sediment supply almost everywhere in the coastal environment. These skeletal contributions can be locally important and may even be the dominant source of sediment. Vegetation, such as mangroves and various grasses, plays an important role in trapping and stabilizing sediments. Growth of aquatic plants in wetlands and estuaries is critical in trapping fine-grained sediments, eventually leading to infilling of these basins (if balances between sediment supply and sea level changes remain steady). Kelp, particularly the larger species, can be an important agent of erosion and transportation of coarse detritus such as gravel and cobble. Biological coasts are discussed in greater detail in Chapter 3. Deltaic and estuarine processes, which are greatly influenced by biology, are discussed in Chapter 4.

2-6. Sea Level Changes

a. Background.

(1) General.

(a) Changes in sea level can have profound influence on the geology, natural ecology, and human habitation of coastal areas. A long-term and progressive rise in sea level has been cited as a major cause of erosion and property damage along our coastlines. Predicting and understanding this rise can guide coastal planners in developing rational plans for coastal development and the design, construction, and operation of structures and waterways.

(b) Many geomorphic features on contemporary coasts are the byproducts of the eustatic rise in sea level caused by Holocene climatic warming and melting of continental glaciers. Sea level has fluctuated throughout geologic time as the volume of ocean water has fluctuated, the shape of the ocean basins has changed, and continental masses have broken apart and re-formed.

(c) Sea level changes are the subject of active research in the scientific community and the petroleum industry. The poor worldwide distribution of tide gauges has hampered the study of recent changes (covering the past century) as most gauges were (and still are) distributed along the coasts of industrial nations in the Northern Hemisphere. Readers interested in this fascinating subject are referred to Emery and Aubrey's (1991) excellent book, *Sea Levels, Land Levels, and Tide Gauges.* This volume and Gorman (1991) contain extensive bibliographies. Tabular data and analyses of United States tide stations are printed in Lyles, Hickman, and Debaugh (1988), and worldwide Holocene sea level changes are documented in Pirazzoli (1991). Papers on sea level fluctuations and their effects on coastal evolution are presented in Nummedal, Pilkey, and Howard (1987). Engineering implications are reviewed in National Research Council (1987). Atmospheric CO_2, climate change, and sea level are explored in National Research Council (1983). Houston (1993) discusses the state of uncertainty surrounding predictions on sea level change.

(2) Definitions. Because of the complexity of this topic, it is necessary to introduce the concepts of relative and eustatic sea level:

(a) *Eustatic* sea level change is caused by change in the relative volumes of the world's ocean basins and the total amount of ocean water (Sahagian and Holland 1991). It can be measured by recording the movement in sea surface elevation compared with some universally adopted reference frame. This is a challenging problem because eustatic measurements must be obtained from the use of a reference frame that is sensitive *only* to ocean water and ocean basin volumes. For example, highly tectonic areas (west coasts of North and South America; northern Mediterranean countries) are not suitable for eustatic sea level research because of frequent vertical earth movements (Mariolakos 1990). Tide gauge records from "stable" regions throughout the world have generated estimates of the recent eustatic rise ranging from 15 cm/century (Hicks 1978) to 23 cm/century (Barnett 1984).

(b) A *relative* change in water level is, by definition, a change in the elevation of the sea surface compared with some local land surface. The land, the sea, or both may have moved in *absolute* terms with respect to the earth's geoid. It is exceptionally difficult to detect absolute sea level changes because tide stations are located on land masses that have themselves moved vertically. For example, if both land and sea are rising at the same rate, a gauge will show that relative sea level (rsl) has not changed. Other clues, such as beach ridges or exposed beach terraces, also merely reflect their movement relative to the sea.

(3) Overview of causes of sea level change.

(a) Short-term sea level changes are caused by seasonal and other periodic or semi-periodic oceanographic factors. These include astronomical tides, movements of ocean currents, runoff, melting ice, and regional atmospheric variations. Included in this category are abrupt land level changes that result from volcanic activity or earthquakes. *Short-term* is defined here as an interval during which we can directly see or measure the normal level of the ocean rising or falling (a generation or 25 years). These factors are of particular pertinence to coastal managers and engineers, who are typically concerned with projects expected to last a few decades and who need to anticipate sea level fluctuations in their planning.

(b) Slow, secular sea and land level changes, covering time spans of thousands or millions of years, have been caused by glacioeustatic, tectonic, sedimentologic, climatologic, and oceanographic factors. Sea level was about 100 to 130 m lower during the last glacial epoch (Figure 2-15), about 15,000 years before present. Ancient shorelines and deltas can be found at such depths along the edge of the continental shelf (Suter and Berryhill 1985). Changes of this magnitude have been recorded during other geological epochs (Payton 1977).

(c) Table 2-6 lists long-term and short-term factors along with estimates of their effect on sea level. The following paragraphs discuss some factors in greater detail.

b. Short-term causes of sea level change.

(1) Seasonal sea level changes.

(a) The most common of the short-term variations is the seasonal cycle, which in most areas accounts for water level changes of 10 to 30 cm (and in some unusual cases - the Bay of Bengal - as much as 100 cm) (Komar and Enfield 1987). Seasonal effects are most noticeable near river mouths and estuaries. Variations in seasonal river flow may account for up to 21 percent of annual sea level variations in coastal waters (Meade and Emery 1971). Compared to the eustatic rise of sea level, estimated to be up to 20 cm/century, the seasonal factor may be a more important cause of coastal erosion because of

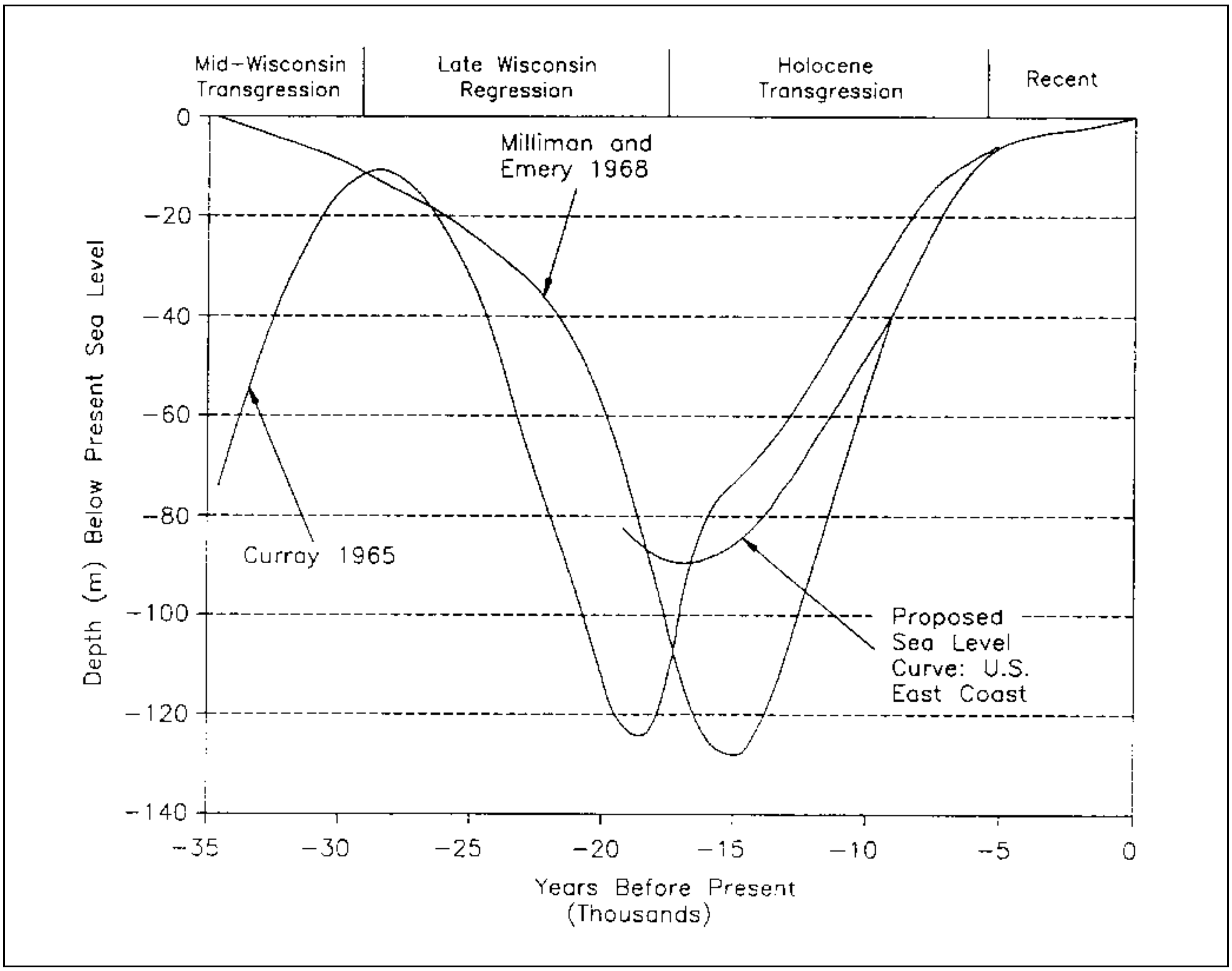

Figure 2-15. Sea level fluctuations during the Pleistocene and Holocene epochs (adapted from Nummedal (1983); data from Dillon and Oldale (1978))

Table 2-6
Sea Level Changes Along the Coastal Zone

Short-Term (Periodic) Causes	Time scale (P = period)	Vertical Effect[1]
Periodic Sea Level Changes		
Astronomical tides	6-12 hr P	0.2-10+ m
Long-period tides		
Rotational variations (Chandler effect)	14 month P	
Meteorological and Oceanographic Fluctuations		
Atmospheric pressure		
Winds (storm surges)	1-5 days	Up to 5 m
Evaporation and precipitation	Days to weeks	
Ocean surface topography (changes in water density and currents)	Days to weeks	Up to 1 m
El Niño/southern oscillation	6 mo every 5-10 yr	Up to 60 cm
Seasonal Variations		
Seasonal water balance between oceans (Atlantic, Pacific, Indian)		
Seasonal variations in slope of water surface		
River runoff/floods	2 months	1 m
Seasonal water density changes (temperature and salinity)	6 months	0.2 m
Seiches	Minutes-hours	Up to 2 m
Earthquakes		
Tsunamis (generate catastrophic long-period waves)	Hours	Up to 10 m
Abrupt change in land level	Minutes	Up to 10 m

Long-Term Causes	Range of Effect Eustatic or Local	Vertical Effect[1]
Change in Volume of Ocean Basins		
Plate tectonics and seafloor spreading (plate divergence/convergence) and change in seafloor elevation (mid-ocean volcanism)	E	0.01 mm/yr
Marine sedimentation	E	< 0.01 mm/yr
Change in Mass of Ocean Water		
Melting or accumulation of continental ice	E	10 mm/yr
Release of water from earth's interior	E	
Release or accumulation of continental hydrologic reservoirs	E	
Uplift or Subsidence of Earth's Surface (Isostasy)		
Thermal-isostasy (temperature/density changes in earth's interior)	L	
Glacio-isostasy (loading or unloading of ice)	L	1 cm/yr
Hydro-isostasy (loading or unloading of water)	L	
Volcano-isostasy (magmatic extrusions)	L	
Sediment-isostasy (deposition and erosion of sediments)	L	< 4 mm/yr
Tectonic Uplift/Subsidence		
Vertical and horizontal motions of crust (in response to fault motions)	L	1-3 mm/yr
Sediment Compaction		
Sediment compression into denser matrix	L	
Loss of interstitial fluids (withdrawal of oil or groundwater)	L	
Earthquake-induced vibration	L	
Departure from Geoid		
Shifts in hydrosphere, aesthenosphere, core-mantle interface	L	
Shifts in earth's rotation, axis of spin, and precession of equinox	E	
External gravitational changes	E	

[1]Effects on sea level are estimates only. Many processes interact or occur simultaneously, and it is not possible to isolate the precise contribution to sea level of each factor. Estimates are not available for some factors. (Sources: Emery and Aubrey (1991); Gornitz and Lebedeff (1987); Komar and Enfield (1987))

its greater year-to-year influence (Komar and Enfield 1987).

(b) Over most of the world, lowest sea level occurs in spring and highest in autumn. Separating the individual factors causing the annual cycle is difficult because most of the driving mechanisms are coherent - occurring in phase with one another. Variations in atmospheric pressure drive most of the annual sea level change (Komar and Enfield 1987).

(2) West coast of North America.

(a) The west coast is subject to extreme and complicated water level variations. Short-term fluctuations are related to oceanographic conditions like the El Niño-Southern Oscillation. This phenomenon occurs periodically when equatorial trade winds in the southern Pacific diminish, causing a seiching effect that travels eastward as a wave of warm water. This raises water levels all along the U.S. west coast. Normally, the effect is only a few centimeters, but during the 1982-83 event, sea level rose 35 cm at Newport, OR (Komar 1992). Although these factors do not necessarily cause permanent geologic changes, engineers and coastal planners must consider their potential effects.

(b) Seasonal winter storms along the Pacific Northwest can combine with astronomical tides to produce elevated water levels over 3.6 m. During the severe storms of 1983, water levels were 60 cm over the predicted level.

(3) Rapid land level changes. Earthquakes are shock waves caused by abrupt movements of blocks of the earth's crust. A notable example occurred during the Great Alaskan Earthquake of 1964, when changes in shoreline elevations ranged from a 10-m uplift to a 2-m downdrop (Hicks 1972; Plafker and Kachadoorian 1966).

(4) Ocean temperature. Changes in the water temperature of upper ocean layers cause changes in water density and volume. As surface water cools, the density of seawater increases, causing a decrease in volume, thus lowering sea level. When temperature increases, the opposite reaction occurs. Variations in water temperature are not simply due to seasonal changes in solar radiation but are primarily caused by changes in offshore wind and current patterns.

(5) Ocean currents. Because of changes in water density across currents, there is a slope of the ocean surface occurring at right angles to the direction of current flow. The result is an increase in height on the right side of the current (when viewed in the direction of flow) in the Northern Hemisphere and to the left in the Southern Hemisphere. The elevation change across the Gulf Stream, for example, exceeds 1 m (Emery and Aubrey 1991). In addition, major currents in coastal areas can produce upwelling, a process that causes deep colder water to move upward, replacing warmer surface waters. The colder upwelled water is denser, resulting in a regional decrease in sea level.

c. Long-term causes of sea level change.

(1) Tectonic instability. Regional, slow land level changes along the U.S. western continental margin affect relative long-term sea level changes. Parts of the coast are rising and falling at different rates. In Oregon, the northern coast is falling while the southern part is rising relative to concurrent relative sea level (Komar 1992).

(2) Isostacy. *Isostatic adjustment* is the process by which the crust of the Earth attains gravitational equilibrium with respect to superimposed forces (Emery and Aubrey 1991). If a gravitational imbalance occurs, the crust rises or sinks to correct the imbalance.

(a) The most widespread geologically rapid isostatic adjustment is the depression of land masses caused by glaciers and the rebounding caused by deglaciation. In Alaska and Scandinavia, contemporary uplift follows the depression of the crust caused by the Pleistocene ice sheets. Some areas of the Alaska coast (for example, Juneau) are rising over 1 cm/year, based on tide gauge records (Figure 2-16) (Lyles, Hickman, and Debaugh 1988).

(b) Isostatic adjustments have also occurred due to changes in sediment load on continental shelves and at deltas. The amount of sediment loading on shelves is not well determined but is probably about 4 mm/yr. The effect is only likely to be important at deltas where the sedimentation rate is very high (Emery and Aubrey 1991).

(3) Sediment compaction.

(a) Compaction occurs when poorly packed sediments reorient into a more dense matrix. Compaction can occur because of vertical loading from other sediments, by draining of fluids from the sediment pore space (usually a man-made effect), by desiccation (drying), and by vibration.

(b) Groundwater and hydrocarbon withdrawal is probably the main cause of sediment compaction on a

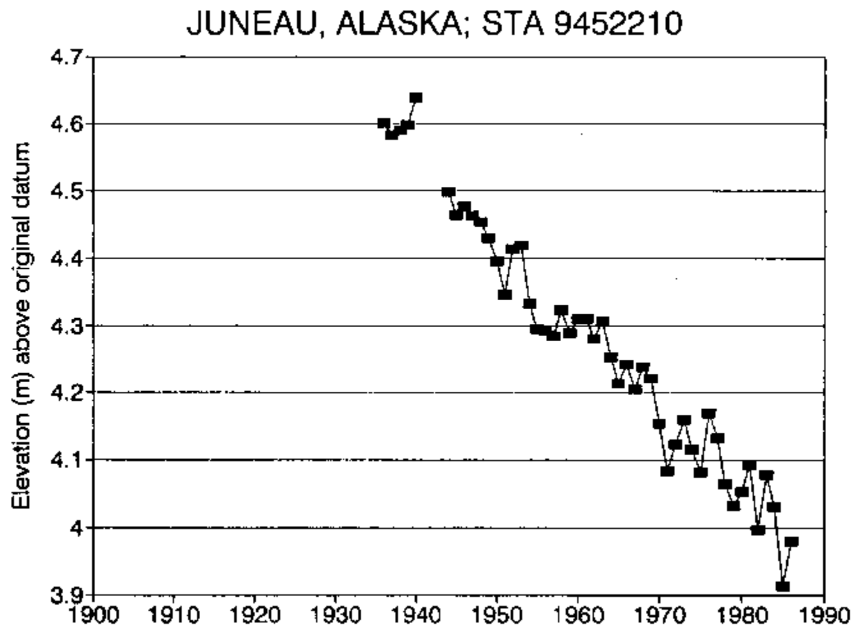

Figure 2-16. Yearly mean sea level changes at Juneau, Alaska, from 1936-1986. The fall in sea level shows the effects of isostatic rebound (data from Lyles, Hickman, and Debaugh (1988))

regional scale. Subsidence exceeding 8 m has been recorded in Long Beach, CA, and over 20 m in the Houston-Freeport area (Emery and Aubrey 1991). In Galveston, the annual sea level rise shown on tide records is 0.6 cm/yr (Figure 2-17) (Lyles, Hickman, and Debaugh 1988). Subsidence at Venice, Italy, caused by groundwater pumping, has been well-publicized because of the threat to architectural and art treasures. Fortunately, subsidence there appears to have stopped now that alternate sources of water are being tapped for industrial and urban use (Emery and Aubrey 1991).

(c) Significant subsidence occurs in and near deltas, where great masses of fine-grained sediment accumulate rapidly. Land loss in the Mississippi delta has become a critical issue in recent years because of the loss of wetlands and rapid shoreline retreat. Along with natural compaction of underconsolidated deltaic muds and silts, groundwater and hydrocarbon withdrawal and river diversion might be factors contributing to the subsidence problems experienced in southern Louisiana. Tide gauges at Eugene Island and Bayou Rigaud show that the rate of subsidence has increased since 1960 (Emery and Aubrey 1991). Change in rsl in the Mississippi Delta is about 15 mm/yr, while the rate at New Orleans is almost 20 mm/yr (data cited in Frihy (1992)).

d. Geologic implications of sea level change.

(1) Balance of sediment supply versus sea level change. Changes in sea level will have different effects on various portions of the world's coastlines, depending on conditions such as sediment type, sediment supply, coastal planform, and regional tectonics. The shoreline position in any one locale responds to the cumulative effects of the various sea level effects (outlined in Table 2-6). For simplicity, these factors can be subdivided into two broad categories: sediment supply and rsl change. Ultimately, shoreline position is a balance between sediment availability and the rate that sea level changes (Table 2-7). For example, at an abandoned distributary of the Mississippi River delta, rsl is rising rapidly because of compaction of deltaic sediment. Simultaneously, wave action causes rapid erosion. The net result is extra rapid shoreline retreat (the upper right box in Table 2-7). The examples in the table are broad generalizations, and some sites may not fit the model because of unique local conditions.

(2) Historical trends. Historical records show the prevalence of shore recession around the United States

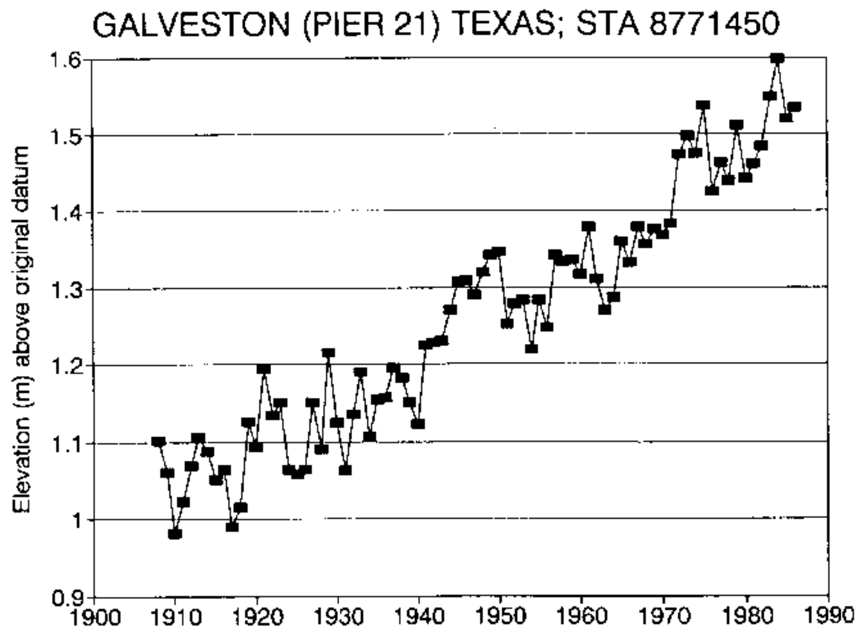

Figure 2-17. Yearly mean sea level changes at Galveston, Texas, from 1908-1986. Subsidence of the land around Galveston may be caused by groundwater withdrawal and sediment compaction (data from Lyles, Hickman, and Debaugh (1988))

during the past century (summarized by the National Research Council (1987):

- National average (unweighted) erosion rate: 0.4 m/yr.
- Atlantic Coast: 0.8 m/yr (with Virginia barrier islands exhibiting the highest erosion rates).
- Gulf Coast: 1.8 m/yr (with highest erosion rate in Louisiana, 4.2 m/yr).
- Pacific coastline: essentially stable (although more than half the shore is hard rock).

Bird (1976) claims that most sandy shorelines around the world have retreated during the past century. Prograding shores occur in areas where rivers supply excess sediment or where tectonic uplift is in progress.

(3) Specific coastal sites.

(a) Sandy (barrier) coasts. Several models predicting the effects of sea level rise on sandy coasts have been proposed. One commonly cited model is the Bruun rule. The Bruun rule and barrier migration models are discussed in Chapter 3, paragraph 3-9.

(b) Cliff retreat. Cliff retreat is a significant problem in the Great Lakes, along the Pacific coast, and in parts of New England and New York. Increases in water level are likely to accelerate the erosion rate along Great Lakes shores (as shown by Hands (1983) for eastern Lake Michigan). However, along southern California, cliff retreat may be episodic, caused by unusually severe winter storms, groundwater and surface runoff, and, possibly, faulting and earthquakes, factors not particularly influenced by sea level (Kuhn and Shepard 1984). Crystalline cliffs are essentially stable because their response time is so much slower than that of sandy shores. Mechanisms of cliff erosion are discussed in Chapter 3, paragraph 3-8.

(c) Marshes and wetlands. Marshes and mangrove forests fringe or back most of the Gulf and Atlantic coastlines. Marshes have the unique ability to grow upward in response to rising sea level. However, although marshes produce organic sediment, at high rates of rsl rise, additional sediment from outside sources is necessary to allow the marshes to keep pace with the rising sea. Salt marshes are described in detail in Chapter 3, paragraph 3-11. Paragraph 3-12 describes wetlands, coral and oyster reefs, and mangrove forest coasts. These shores have the natural ability to adjust to changing sea level as long as they are not damaged by man-made factors like urban runoff or major changes in sediment supply.

Table 2-7
Relative Effects of Sediment Supply Versus Sea Level Change on Shoreline Position

		Relative Sea Level Change				
		Falling sea level		**Stable**	**Rising sea level**	
		Rapid	**Slow**		**Slow**	**Rapid**
Sediment supply	**Rapid net loss**	Neutral	Slow retreat	Medium retreat	Rapid retreat[4]	Extra rapid retreat[2]
	Slow net loss	Slow advance	Neutral	Slow retreat	Medium retreat[6]	Rapid retreat
	Zero net change	Medium advance	Slow advance	Neutral[8]	Slow retreat	Medium retreat
	Low net deposition	Rapid advance	Medium advance[10]	Slow advance[7]	Neutral[3,5]	Slow retreat
	Rapid net deposition	Extra rapid advance	Rapid advance[9]	Medium advance	Slow advance[1]	Neutral

Examples of long-term (years) transgression or regression:

1. Mississippi River Delta - active distributary
2. Mississippi River Delta - abandoned distributary
3. Florida Panhandle between Pensacola and Panama City
4. Sargent Beach, TX
5. Field Research Facility, Duck, NC
6. New Jersey shore
7. Island of Hawaii - volcanic and coral sediment supply
8. Hawaiian Islands without presently active volcanoes
9. Alaska river mouths
10. Great Lakes during sustained fall in water levels

(Table based on a figure in Curray (1964))

e. Engineering and social implications of sea level change.

(1) Eustatic sea level rise.

(a) Before engineering and management can be considered, a fundamental question must be asked: Is sea level still rising? During the last decade, the media has "discovered" global warming, and many politicians and members of the public are convinced that greenhouse gases are responsible for rising sea level and the increased frequency of flooding that occurs along the coast during storms. The Environmental Protection Agency created a sensation in 1983 when it published a report linking atmospheric CO_2 to a predicted sea level rise of between 0.6 and 3.5 m (Hoffman, Keyes, and Titus 1983). Since then, predictions of the eustatic rise have been falling, and some recent evidence suggests that the rate may slow or even that eustatic sea level may drop in the future (Houston 1993).

(b) Possibly more reliable information on Holocene sea level changes can be derived from archaeological sites, wave-cut terraces, or organic material. For example, Stone and Morgan (1993) calculated an average rise of 2.4 mm/year from radiocarbon-dated peat samples from Santa Rosa Island, on the tectonically stable Florida Gulf coast. However, Tanner (1989) states that difficulties arise using all of these methods, and that calculated dates and rates may not be directly comparable.

(c) Based on an exhaustive study of tide records from around the world, Emery and Aubrey (1991) have concluded that it is not possible to assess if a *eustatic* rise is continuing because, while many gauges do record a recent rise in *relative* sea level, an equal number record a fall. Emery and Aubrey state (p. ix):

> In essence, we have concluded that 'noise' in the records produced by tectonic movements and both meteorological and oceanographic factors so obscures any signal of eustatic rise of sea level that the tide gauge records are more useful for learning about plate tectonics than about effects of the greenhouse heating of the atmosphere, glaciers, and ocean water.

They also state (p. 176):

> This conclusion should be no surprise to geologists, but it may be unexpected by those climatologists and laymen who have been biased too strongly by the public's perception of the greenhouse effect on the environment....Most coastal instability can be attributed to tectonism and documented human activities without invoking the spectre of greenhouse-warming climate or collapse of continental ice sheets.

(d) In summary, despite the research and attention devoted to the topic, the evidence about worldwide, eustatic sea level rise is inconclusive. Estimates of the rate of rise range from 0 to 3 mm/year, but some researchers maintain that it is not possible to discover a statistically reliable rate using tide gauge records. In late Holocene time, sea level history was much more complicated than has generally been supposed (Tanner 1989), suggesting that there are many perturbations superimposed on "average" sea level curves. Regardless, the topic is sure to remain highly controversial.

(2) Relative sea level (rsl) changes.

(a) The National Research Council's Committee on Engineering Implications of Changes in Relative Sea Level (National Research Council 1987) examined the evidence on sea level changes. They concluded that rsl, on statistical average, is rising at most tide gauge stations located on continental coasts around the world. In their executive summary, they concluded (p. 123):

> The risk of accelerated mean sea level rise is sufficiently established to warrant consideration in the planning and design of coastal facilities. Although there is substantial local variability and statistical uncertainty, average relative sea level over the past century appears to have risen about 30 cm relative to the East Coast of the United States and 11 cm along the West Coast, excluding Alaska, where glacial rebound has resulted in a lowering of relative sea level. Rates of relative sea level rise along the Gulf coast are highly variable, ranging from a high of more than 100 cm/century in parts of the Mississippi delta plain to a low of less than 20 cm/century along Florida's west coast.

However, they, too, noted the impact of management practices:

> Accelerated sea level rise would clearly contribute toward a tendency for exacerbated beach erosion. However, in some areas, anthropogenic effects, particularly in the form of poor sand management practices at channel entrances, constructed or modified for navigational purposes, have resulted in augmented erosion rates that are clearly much greater than would naturally occur. Thus, for some years into the future, sea level rise may play a secondary role in these areas.

(b) Figure 2-18 is a summary of estimates of local rsl changes along the U.S. coast (National Research Council 1987). Users of this map are cautioned that the figures are based on tide records only from 1940-1980 and that much regional variability is evident. The figure provides general information only; for project use, detailed data should be consulted, such as the tide gauge statistics printed in Lyles, Hickman and Debaugh (1988) (examples from two tide stations are plotted in Figures 2-16 and 2-17).

(3) Engineering response and policy.

(a) Whatever the academic arguments about eustatic sea level, engineers and planners must anticipate that changes in rsl may occur in their project areas and need to incorporate the anticipated changes in their designs and management plans.

(b) Because of the uncertainties surrounding sea level, USACE has not endorsed a particular rise (or fall) scenario. Engineer Regulation ER 1105-2-100 (28 December 1990) states the official USACE policy on sea level rise. It directs that:

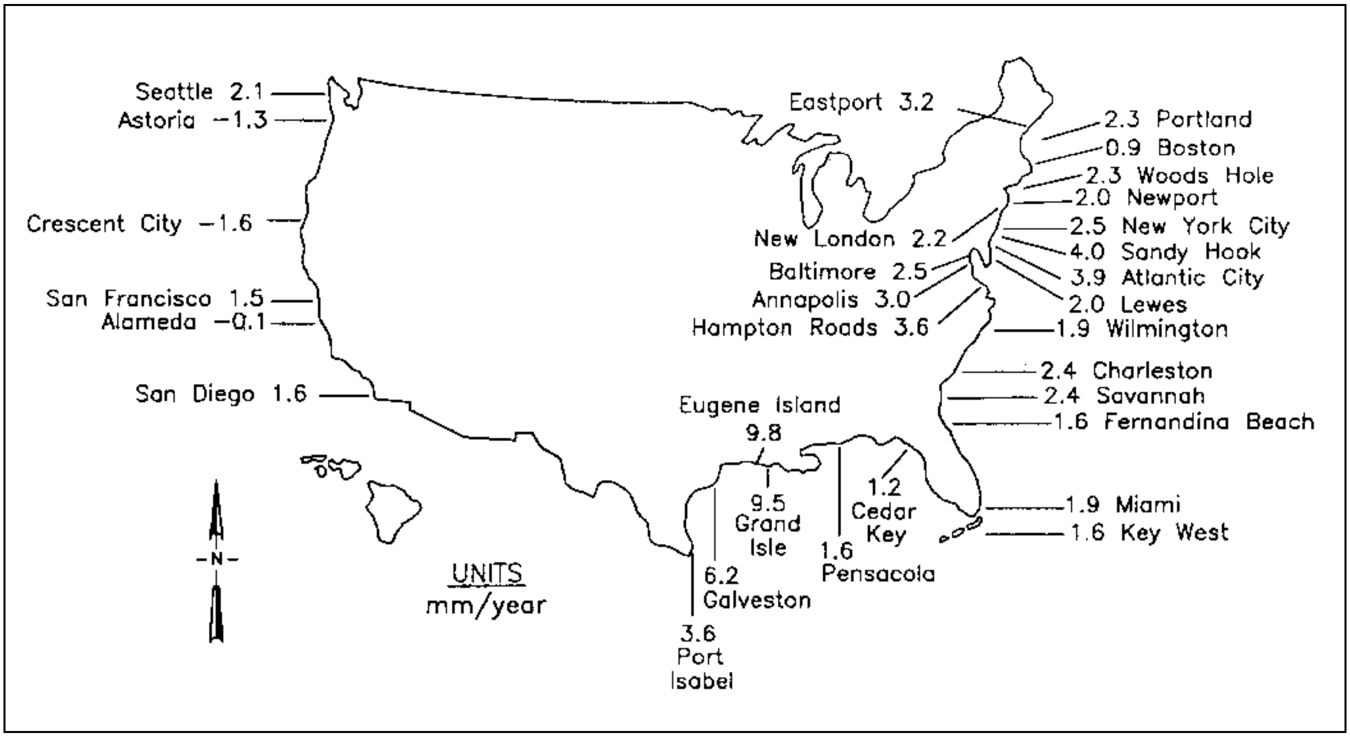

Figure 2-18. Summary of estimates of local rsl rise along the continental Unites States in millimeters per year. Values are based on tide gauge records during the period 1940-1980 (from National Research Council (1987))

> Feasibility studies should consider which designs are most appropriate for a range of possible future rates of rise. Strategies that would be appropriate for the entire range of uncertainty should receive preference over those that would be optimal for a particular rate of rise but unsuccessful for other possible outcomes.

Potential rsl rise should be considered in every coastal and estuarine (as far inland as the new head of tide) feasibility study that USACE undertakes. Project planning should consider what impact a higher rsl rise would have on designs based on local, historical rates.

(3) Impacts of rising sea level on human populations.

(a) Rising sea level raises the spectre of inundated cities, lost wetlands, and expensive reconstruction of waterways and ports. About 50 percent of the U.S. population lives in coastal counties (1980 census data reported in Emery and Aubrey (1991)), and the number is likely to increase. There has not been a long history of understanding and planning for sea level rise in the United States, but other countries, particularly Holland and China, have coped with the problem for thousands of years (National Research Council 1987). There are three principal ways that people could adapt to rising sea level:

- Retreat and abandonment.
- Erecting dikes and dams to keep out the sea.
- Construction on landfills and piers.

(b) Among the areas most susceptible to inundation caused by rise in rsl are deltas. Deltas are naturally sinking accumulations of sediment whose subaerial surface is a low-profile, marshy plain. Already, under present conditions, subsidence imposes especially severe hardships on the inhabitants in coastal Bangladesh (10 mm/yr) and the Nile Delta (2 mm/yr), two of the most densely populated regions on earth (Emery and Aubrey 1991). Even a slow rise in sea level could have devastating effects. How could these areas be protected? Thousands of kilometers of seawalls would be needed to protect a broad area like coastal Bangladesh from the sea and from freshwater rivers. Civil works projects on this scale seem unlikely, suggesting that retreat will be the only recourse (National Research Council 1983). Nevertheless, despite the immense cost of large-scale coastal works, the Netherlands has reclaimed from the sea a large acreage of land, which is now used for towns and agriculture.

(c) Retreat can be either a gradual (planned or unplanned) process, or a catastrophic abandonment (National Research Council 1987). The latter has occurred in communities where buildings were not allowed to be rebuilt after they were destroyed or damaged by storms. The State of Texas followed this approach on Galveston Island after Hurricane Alicia in 1983 and the State of Rhode Island for south shore communities after the Great Hurricane of 1938. Construction setback lines represent a form of controlled retreat. Seaward of setback lines, new construction is prohibited. City managers and coastal planners often have difficulty in deciding where setback lines should be located, and their decisions are usually contested by property developers who wish to build as close to the beach as possible.

(d) Most of the world's coastal cities are subject to inundation with even a modest rise of sea level. Irresistible political pressure will surely develop to defend cities against the rising sea because of the high concentration of valuable real estate and capital assets. Defense will most probably take the form of dikes like the ones that protect large portions of Holland and areas near Tokyo and Osaka, Japan, from flooding. Dikes would be needed to protect low-lying inland cities from rivers whose lower courses would rise at the same rate as the sea. Already, New Orleans (which is below sea level), Rotterdam, and other major cities located near river mouths are kept dry by protective levees. These levees might have to be raised under the scenario of rising sea level. Storm surge barriers, like the ones at New Bedford, MA, Providence, RI, and the Thames, below London, England, might have to be rebuilt to maintain an adequate factor of safety.

(e) Landfilling has historically been a common practice, and many coastal cities are partly built on landfill. Boston's waterfront, including the airport and the Back Bay, is built on 1800's fill (Figure 2-19). Large areas around New York City, including parts of Manhattan and Brooklyn, have been filled since the 1600's (Leveson 1980). In the early 1700's, Peter the Great built his monumental new capital of Saint Petersburg on pilings and fill in the estuary of the Neva River. Artificial land, which is usually low, is particularly susceptible to rising sea level. Although dikes and levees will probably be the most common means to protect cities threatened by the rising sea, there is a U.S. precedent for raising the level of the land surface where structures already exist: Seattle's downtown was raised about 3 m in the early 1900's to prevent tidal flooding. The elevated streets ran along the second floor of buildings, and the original sidewalks and store fronts remained one floor down at the bottom of open troughs. Eventually, the open sidewalks had to be covered or filled because too many pedestrians and horses were injured in falls.

f. Changes in sea level - summary.

(1) Changes in sea level are caused by numerous physical processes, including tectonic forces that affect land levels and seasonal oceanographic factors that influence water levels on various cycles (Table 2-5). Individual contributions of many of these factors are still unknown.

(2) Estimates of the eustatic rise in sea level range from 0 to 3 mm/year. Emery and Aubrey (1991) have strongly concluded that it is not possible to detect a statistically verifiable rate of eustatic sea level rise because of noise in the signals and because of the poor distribution of tide gauges worldwide.

(3) Arguments regarding eustatic sea level changes may be more academic than they are pertinent to specific projects. The rate of *relative* sea level change varies greatly around the United States. Coastal planners need to consult local tide gauge records to evaluate the potential movement of sea level in their project areas.

(4) In many areas, coastal management practices have the greatest influence on erosion, and sea level changes are a secondary effect (Emery and Aubrey 1991; National Research Council 1987).

(5) The USACE does not endorse a particular sea level rise (or fall) scenario. Engineer Regulation ER 1105-2-100 (28 December 1990) directs that feasibility studies must consider a range of possible future rates of sea level rise. Project planning should use local, historical rates of rsl change.

2-7. Cultural (Man-Made) Influences on Coastal Geology

a. Introduction. Man has modified many of the world's coastlines, either directly, by construction or dredging, or indirectly, as a result of environmental changes that influence sediment supply, runoff, or climate. Human activity has had the most profound effects on the coastal environment in the United States and the other

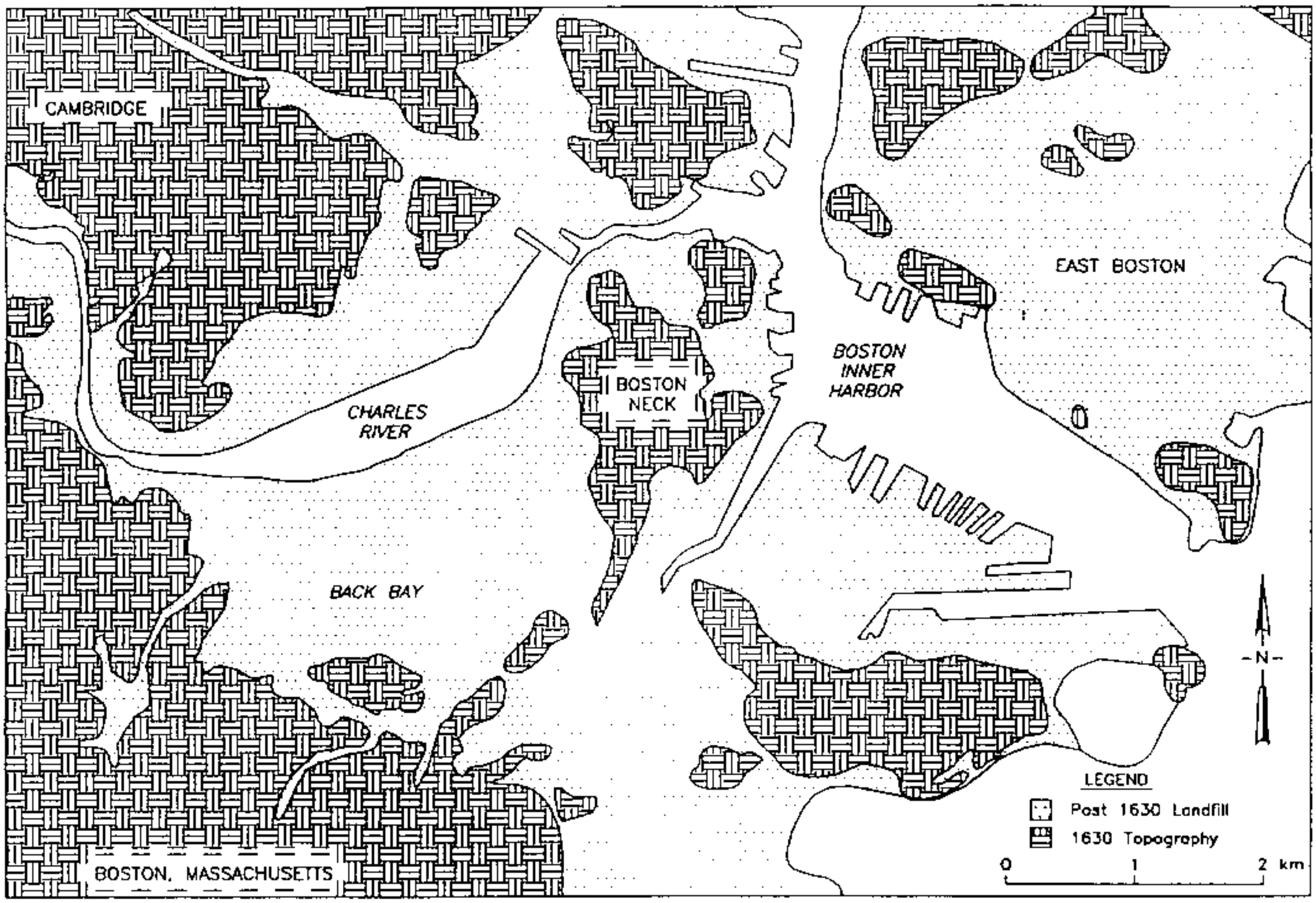

Figure 2-19. Landfilling in Boston, MA, since 1630 has more than doubled the urban area (unfortunately, at the expense of destroying what must have been highly productive wetlands) (from Rosen, Brenninkmeyer, and Maybury 1993)

industrial nations, but even shorelines in lesser-developed, agricultural countries have not been immune to problems wrought by river diversion and loss of wetlands. The most common practices that significantly alter the coastal environment are the construction of coastal works such as jetties and groins and the development of property on and immediately inland of the beach. Historically, many cities have developed on the coast. Although originally most were located in bays or other protected anchorages, many have grown and spread to the open coast. Prominent examples include New York, Boston, San Diego, and Los Angeles. Still other communities originally began as resorts on barrier islands and have since grown into full-size cities; examples include Atlantic City, Ocean City, Virginia Beach, and Miami Beach. Land use practices well inland from the coast also often have important effects on coastal sedimentation. These factors are more difficult to detect and analyze because, sometimes, the affecting region is hundreds of kilometers inland. For example, dam construction can greatly reduce the natural supply of sediment brought to the coast by streams and rivers, while deforestation and agricultural runoff may lead to increased sediment load in rivers.

b. Dams/Reservoirs. In many coastal areas, the major source of sediment for the littoral system is from streams and rivers (*Shore Protection Manual* 1984). Dams and reservoirs obstruct the transport of sediment to the littoral system by creating sediment traps. These structures also restrict peak flows, which reduce sediment transport of material that is available downstream of the structures. The net effect is sediment starvation of coastal areas that normally receive riverine sediment. If the losses are not offset by new supplies, the results are shrinking beaches and coastal erosion (Schwartz 1982). The most prominent example is the accelerated erosion of the Nile Delta since the Aswan Low Dam (1902) and the Aswan High Dam (1964) almost totally blocked the supply of sediment to the coast (Frihy 1992). The Rosetta promontory has been eroding at an average rate of

55 m/yr between 1909 and the present. Loss of nutrient-laden silt from the Nile's annual spring floods has also had bad effects on agriculture in the Nile valley and delta and has damaged fisheries in the eastern Mediterranean. Portions of the southern California coast have also suffered this century from loss of fluvially supplied sediment (e.g., Point Arguello, cited by Bowen and Inman (1966)).

c. Erosion control and coastal structures. Coastal structures such as jetties, groins, seawalls, bulkheads, and revetments are probably the most dramatic cause of man-induced coastal erosion (*Shore Protection Manual* 1984). Structures are broadly subdivided into several general classes:

- Seawalls and bulkheads intended to prevent erosion along cliffs and slopes.
- Groins built perpendicular to the coast to trap littoral drift.
- Breakwaters designed to protect inlets and harbors.

The following paragraphs briefly discuss coastal geologic effects caused by these structures.

(1) Seawalls, bulkheads, and revetments. These structures have traditionally been placed along a threatened stretch of coastline to prevent erosion or reduce undercutting of cliffs. Seawalls cause a range of environmental problems. Because they are static features, they are unable to respond to dynamic beach changes and typically impede land-sea sediment interchange (Carter 1988). On the beach (seaward) side of seawalls, wave reflection tends to transport material seaward, and it is common for the beach to drop in level over time. Examples of United States seawalls where the formerly protective beaches have eroded include Revere, MA, and Galveston, TX. Problems may also occur on the landward side of seawalls if drainage of groundwater is not adequate. Increased pore pressure may lead to instability and cliff failure (Kuhn and Shepard 1984). Critical erosion problems can occur near the ends of seawalls if they are not properly tied in to the adjacent shoreline. Waves erode the unprotected shore, eventually causing an embayment to form. With time, the embayment grows, enveloping the end of the seawall and exposing the formerly protected backshore to erosion. A spectacular example of the "terminal scour" problem is at Cape May, New Jersey, where erosion has caused shoreline retreat of over 1 km and resulted in the destruction of the village of South Cape May (Carter 1988).

(2) Shore-normal structures - jetties and groins.

(a) *Groins* are usually installed to prevent or reduce the rate of erosion along a particular stretch of the shore. Their purpose is to interrupt the longshore transport of littoral material, trapping sediment that would naturally move downdrift. Unfortunately, groins typically accomplish little to cure the root causes of the erosion problem in a particular area (i.e., a lack of sediment, often made worse by updrift groin fields). Terminal groins have proven useful in stabilizing shores in specific locations, such as at inlets or the ends of littoral cells. There are many environmental disadvantages to groins, the most obvious being sediment starvation downdrift. Unfortunately, many local communities have fallen prey to exaggerated claims of the efficacy of groins in solving their erosion problems.

(b) *Jetties* are structures, generally built perpendicular to the shore, designed to direct and confine tidal or riverine flow to a selected channel to prevent or reduce shoaling of that channel. Jetties also protect inlets and harbor mouths from storm waves. There are hundreds of navigation projects in the United States protected by jetties. Jetties often cause or contribute to local geologic effects (which may not occur at all sites):

- Jetties often interrupt littoral drift, allowing sediment to accumulate updrift and causing sand starvation downdrift.
- Inlet mouths are stabilized, preventing migration.
- Tidal prisms may change because of the presence of the permanent and maintained channel. This can affect salinity, flushing, and nutrient and larval exchanges between the sea and the bay.
- Sediment flow in and out of tidal inlets may be interrupted, leading to sediment starvation in some cases and excessive shoaling in others.
- Ebb-tidal shoal growth is often enhanced after jetty construction and stabilization of the channel mouth.

Some of these effects are not caused solely by the jetties but are also a result of dredging, ship traffic, and other aspects of a maintained navigation channel. Inlets are discussed in greater detail in Chapter 4, paragraph 4-4. Design of breakwaters and jetties is covered in EM 1110-2-2904.

d. Modification of natural protection.

(1) Destructive effects. The destruction of dunes and beach vegetation, development of backshore areas, and construction on the back sides of barrier islands can increase the occurrence of overwash during storms. In many places, sand supply has diminished because much of the surface area of barriers has been paved or covered with buildings. The result has been backshore erosion and increased breaching of barrier islands. In most coastal areas of the United States, one need merely visit the local beaches to see examples of gross and callous coastal development where natural protection has been compromised. Carter (1988) reviews examples from the United Kingdom. Serious damage has occurred to biological shores around the world as a result of changes in runoff and sediment supply, increased pollution, and development.

(2) Constructive efforts. Sand dunes are often stabilized using vegetation and sand fences. Dunes afford protection against flooding of low-lying areas. Dunes are also stabilized to prevent sand from blowing over roads and farms. Dunes are discussed in Chapter 3, paragraph 3-6.

e. Beach renourishment. An alternative for restoring beaches without constructing groins or other hard structures is to bring sand to the site from offshore by dredges or from inland sources by truck. Although conceptually renourishment seems simple enough, in practice, the planning, design, application, and maintenance of beach renourishment projects are sophisticated engineering and geologic procedures. Beach fill design is not covered in this manual. For design and monitoring information, the reader is referred to the *Shore Protection Manual* (1984), Tait (1993), and Stauble and Kraus (1993). *Shore and Beach*, Vol 61, No. 1 (January 1993) is a special issue devoted to the beach renourishment project at Ocean City, MD. Stauble et al. (1993) evaluate the Ocean City project in detail. Krumbein (1957) is a classic description of sediment analysis procedures for specifying beach fills. One of the most successful U.S. renourishment projects has been at Miami Beach, FL (reviewed in Carter (1988)).

f. Mining.

(1) Beach mining can directly reduce the amount of sediment available to the littoral system. In many areas of the United States, beach sand can no longer be exploited for commercial purposes because sand is in short supply on many shores, and the health of dunes and biological communities depends vitally on the availability of sand. Strip mining can indirectly affect the coast due to increased erosion, which increases sediment carried to the sea by rivers (unless the sediment is trapped behind dams).

(2) In Britain, an unusual situation developed at Horden, County Durham, where colliery waste was dumped on the shore. The waste material formed a depositional bulge in the shore. As the sediment from Horden moves downcoast, it has been sorted, with the less dense coal forming a surface placer on the beach that is commercially valuable (Carter 1988).

g. Stream diversion.

(1) Stream diversion, both natural and man-made, disrupts the natural sediment supply to areas that normally receive fluvial material. With diversion for agriculture or urban use, the results are similar to those produced by dams: sediment that normally would be carried to the coast remains trapped upriver. Its residence time in this artificial storage, decades or centuries, may be short on geological time scales but is long enough to leave a delta exposed to significant erosion.

(2) Natural diversion occurs when a river shifts to a new, shorter channel to the sea, abandoning its less-efficient former channel. An example of this process is the gradual occupation of the Atchafalaya watershed by the Mississippi River. If this process were to continue to its natural conclusion, the present Balize ("Birdfoot") delta would be abandoned, causing it to erode at an ever faster rate, while a new delta would form in Atchafalaya Bay (Coleman 1988). The evolution of the Mississippi River is discussed in Chapter 4, paragraph 4-3.

h. Agriculture. Poor farming practices lead to exposure of farmlands and increased erosion rates. Eroded soil is easily carried away by streams and rivers and is ultimately deposited in estuaries and offshore. The consequence of this process is accretion and progradation of the depositional areas.

i. Forestry. Deforestation is a critical problem in many developing nations, where mountainsides, stripped of their protective trees, erode rapidly. The soil is carried to the sea, where local coastlines prograde temporarily, but upland areas are left bereft of invaluable topsoil, resulting in human poverty and misery and in the loss of animal habitat. Reckless slash-and-burn practices have destroyed many formerly valuable timber resources in Central America, and some southeast Asian countries have already cut down most of these trees (Pennant-Rea

1994). Fortunately, Malaysia and Indonesia are beginning to curb illegal timber cutting and export, a trend which hopefully will spread to other countries.