From Anikouchine and Sternberg — "The World Ocean" Prentice-Hall

ONE
TWO
THREE
FOUR
FIVE
SIX
SEVEN
EIGHT
NINE
TEN
ELEVEN
TWELVE
THIRTEEN
FOURTEEN
FIFTEEN

# *inshore* *oceanography*

At the coastal zone of the world ocean, air, water, and solid earth meet; and there is endless interaction among the geological, biological, meteorological, and oceanic processes. Each of these environmental processes affects the nature of a coastal region to some degree. Consequently, a study of the processes at work in a coastal sector can help us understand the origin, relative age, and history of that coast.

## 10 THE OPEN COAST

### OCEANIC INFLUENCE

The diverse influences of ocean waters upon coastal features are related to both the physical attributes of seawater (i.e., waves, currents, and turbulence) and the chemical properties (i.e., solubility and concentration). The effect of ocean waves, however, is the most important. The configuration of a coastal area and the offshore floor of the sea is largely the result of wave action. For this reason, the properties of shoaling waves are emphasized in this section.

Nearshore Circulation. As waves carry energy toward shore, they encounter shallow water and their speed of propagation decreases. If the

A large ocean
a complex coa
courtesy of

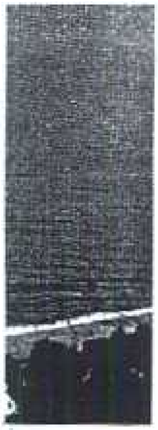

A

Photo (A
zone. The d

direction of
ward part of
occurs (Fig.
causes wave
this alignme
pletely parall
offshore profi

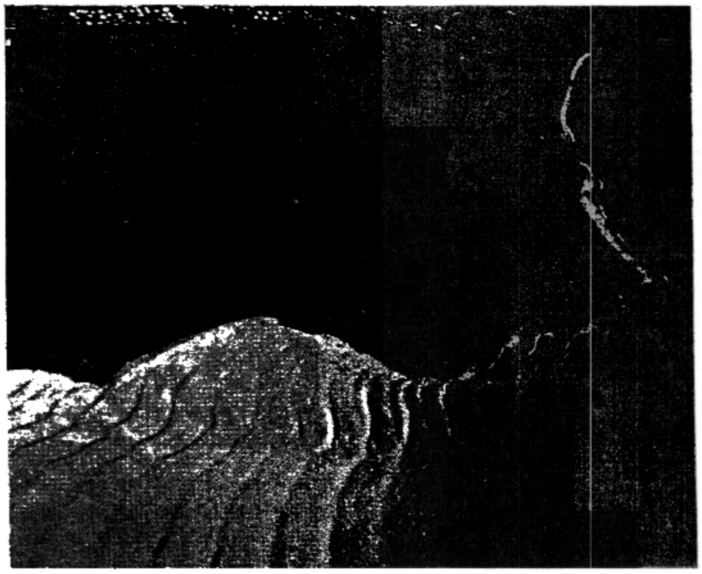


**Figure 10-1**
A large ocean swell refracts against a complex coastline. (Photograph courtesy of Barbee Scheibner).

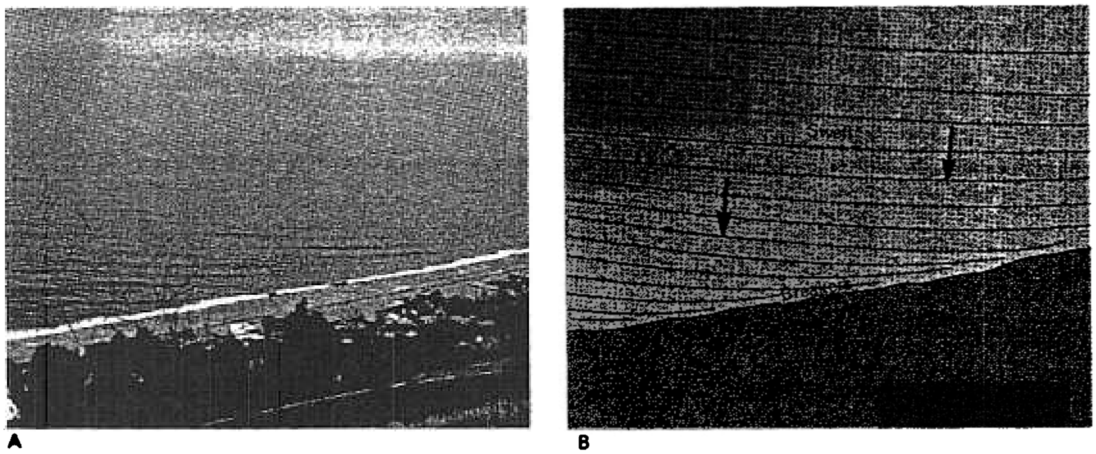


**Figure 10-2**
Photo (A) and line drawing (B) of wave refraction just seaward of the surf zone. The direction of longshore currents is from right to left along the beach.

direction of wave attack is not perpendicular to the shoreline, the shoreward part of a wave slows more than the seaward portion and *refraction* occurs (Fig. 10-1). Figure 10-2 shows how the process of refraction causes wave crests to align themselves parallel to the shoreline. However, this alignment is only a tendency. Wave crests seldom become completely parallel to the shore except where the beach has a long, gentle offshore profile.

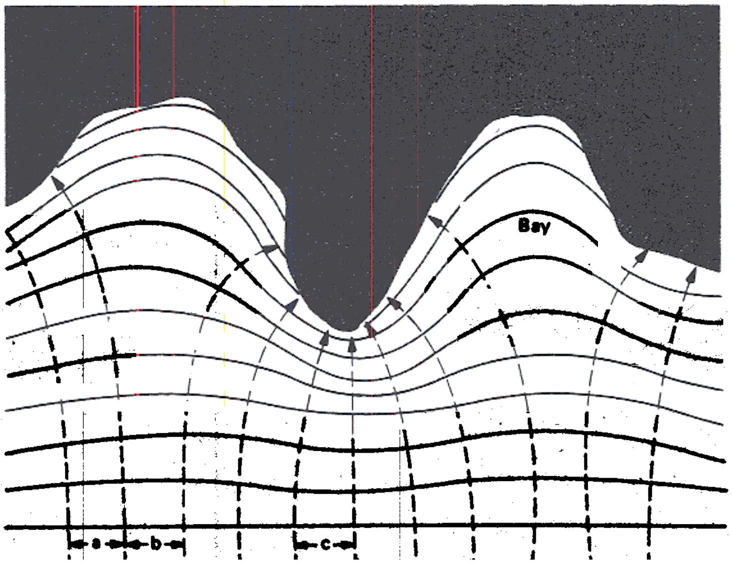
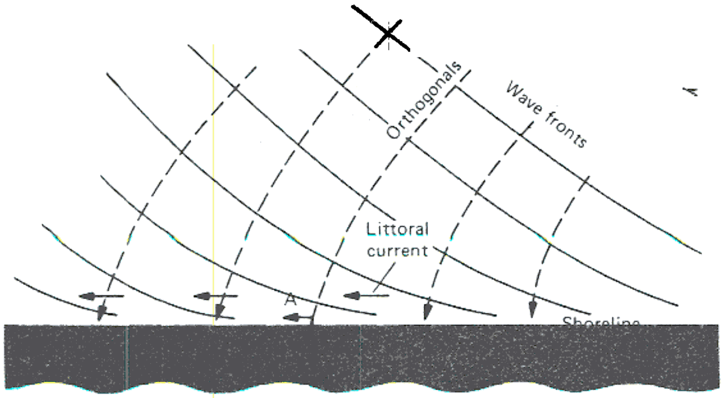


**Figure 10-3**
Schematic of refraction on an irregular coast. Waves are approaching parallel to the coastal trend. Solid lines represent wave crests. Dashed lines are wave orthogonals. (After A. N. Strahler, 1963).

The behavior of waves in expending their energy on a beach can be illustrated by the use of *orthogonals*. These are imaginary lines drawn in such a way that they divide the crest of an unrefracted wave into equal segments of length and energy. Orthogonals are always perpendicular to wave crests and thus show the direction of wave propagation (Fig. 10-3). At the same time, orthogonals indicate the distribution of energy in a wave train; the amount of energy contained between any pair of orthogonals is assumed to be constant regardless of refraction. Where waves attack an

**Figure 10-4**
Direction of littoral currents resulting from waves breaking at an angle to the shore.



irregular coastl
focused on it;
amount of ene
However, this
shorter stretch
coastline is inc
effect is that
time, it tends t
of wave attack.
As a wa
continually inc
ally, the crest
considerations
when either of
than 1.28 time
passes 1/7. A
tensely turbule
rather than os
the beach is
under the influ
water from the
doing, the onc
The tra
the waves wer
is resolved to
along the bea
backwash, wh
*shore*, or *littor*
current is rela
of approach.
the stronger th
On an
lands toward
of longshore
This accumul
which moves
This e
nate. Actuall
mulates in th
Several factor

---

* Depending on
wave are often
times as it a
previous one.

irregular coastline, a point of land refracts the waves so that energy is focused on it; an embayment has the opposite effect. In Fig. 10-3, the amount of energy moving onshore is the same for sections A, B, and C. However, this energy is spread over a longer stretch of beach at B and a shorter stretch of beach at C; consequently, the energy per unit length of coastline is increased in section C and decreased in section B. The net effect is that wave erosion is greater on the headlands. Given enough time, it tends to straighten an irregular coastline, regardless of the direction of wave attack.

As a wave approaches shore, the orbital velocity at the wave crest continually increases, whereas the propagation speed decreases. Eventually, the crest "overruns" the trough, and the wave breaks. Theoretical considerations as well as field observations indicate that breaking occurs when either of two conditions are met: (1) the water depth becomes less than 1.28 times the wave height, or (2) the wave steepness ($H/L$) surpasses 1/7. After a wave breaks, the water-particle motion becomes intensely turbulent, and energy approaches the beach in a wave of translation rather than oscillation.* The mass of turbulent water that moves upon the beach is called *swash*. The water that runs back down the beach under the influence of gravity is termed *backwash*. Backwash removes the water from the beach and causes it to oppose the oncoming waves. In so doing, the oncoming waves are steepened and break a bit sooner.

The transport of water inside the breaker zone is in the direction the waves were traveling just prior to breaking. In Fig. 10-4, the transport is resolved to show a component onto the beach ($B$) and a component along the beach ($A$). The upbeach transport (swash) is balanced by backwash, whereas the transport of water along the beach forms a *longshore*, or *littoral, current*. The quantity of water transported by a littoral current is related to the character of the approaching waves and the angle of approach. The larger the waves or the greater the angle of approach, the stronger the longshore current.

On an irregular shoreline, the net movement of water is from headlands toward embayments (Fig. 10-5). As a result, there is a *convergence* of longshore currents at the mouth of a bay where water accumulates. This accumulation causes a narrow, swift current, called a *rip current*, which moves seaward from the convergence zone (Fig. 10-6).

This example shows only one way in which rip currents may originate. Actually, they are associated with any situation where water accumulates in the surf zone to a point where the excess water flows seaward. Several factors can cause such accumulation: converging longshore cur-

---

* Depending on the way in which breaking occurs, the oscillatory characteristics of a wave are often maintained to the extent that the wave may reform and break several times as it approaches the beach. Each succeeding breaker is smaller than the previous one.

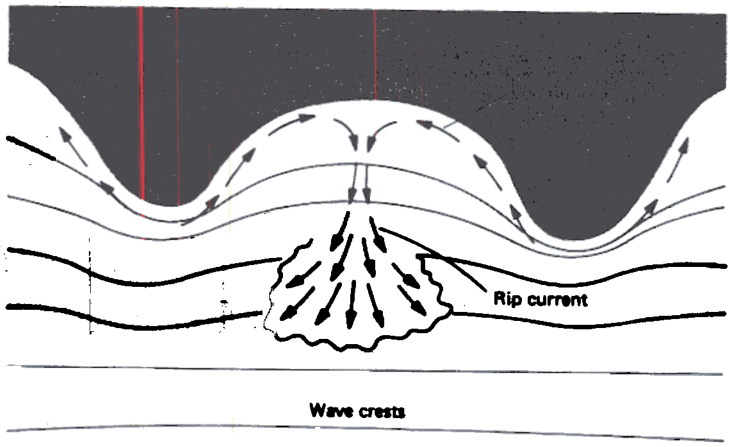
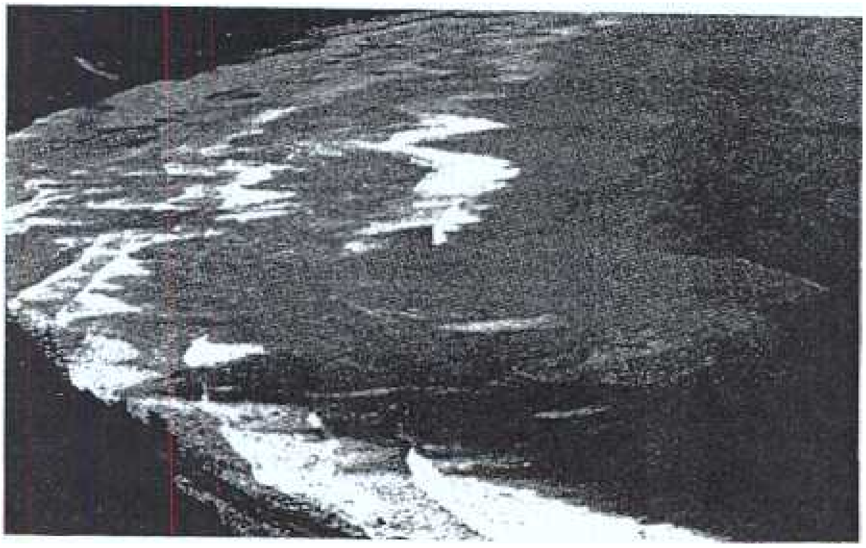


FIGURE 10-5
Net movement of water in an embayment cause rip currents to form.

rents; a physical obstruction to longshore currents, such as a rock groin (a barrier, illustrated in Fig. 10-18), breakwater, or headland; or just the continuous addition of water from breakers approaching parallel to the beach. Rip currents can be recognized in several ways: discoloration due to suspended sand, premature steepening of the approaching waves and the seaward displacement of the breaker line, or the accumulation of foam at the head of the rip. A small cusp of sand may also occur on the beach where the convergence or obstruction occurs.

FIGURE 10-6
Photograph of rip currents in an embayment.



Some ri
width where th
These currents
of their velocity
The wel
as shown in Fi
may last only a
single cause of
(also called an
parallel to the s
current; the lat
To sum
line is the for
wave approach
by the waves a
within the surf
lands) to low

NEARSH
tem is very eff
the coastline
longshore curr
of suspension
*shore*, or *litto*
pirically that
wave energy e
Moving

Schematic
(From

Some rip currents extend as far as 1000 m offshore, are 30 m in width where they flow through the surf, and travel up to 100 cm per sec. These currents carry sand as well as excess water from the beach. Because of their velocity, they often erode shallow channels through the surf zone.

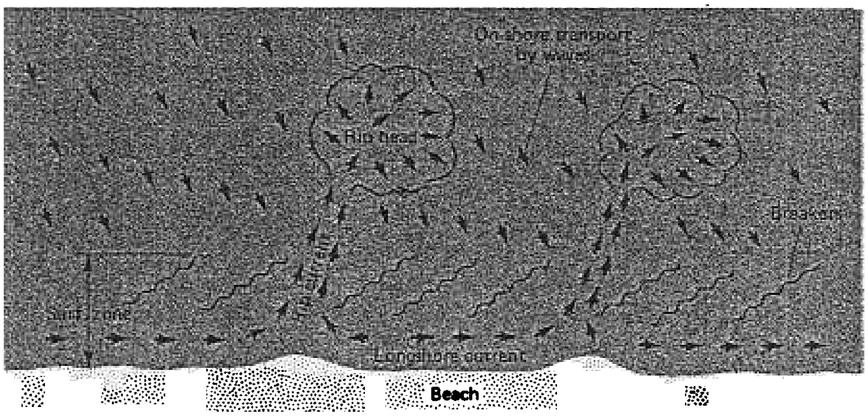
The well-developed rip-current system exhibits a circulation pattern as shown in Fig. 10-7. Rip currents may be semipermanent features or may last only a few hours or a few days. They are probably the greatest single cause of drownings on a beach. A swimmer caught in a rip current (also called an *undertow*) can escape being swept out to sea if he swims parallel to the shore rather than trying to swim against the direction of the current; the latter recourse only enhances the possibility of exhaustion.

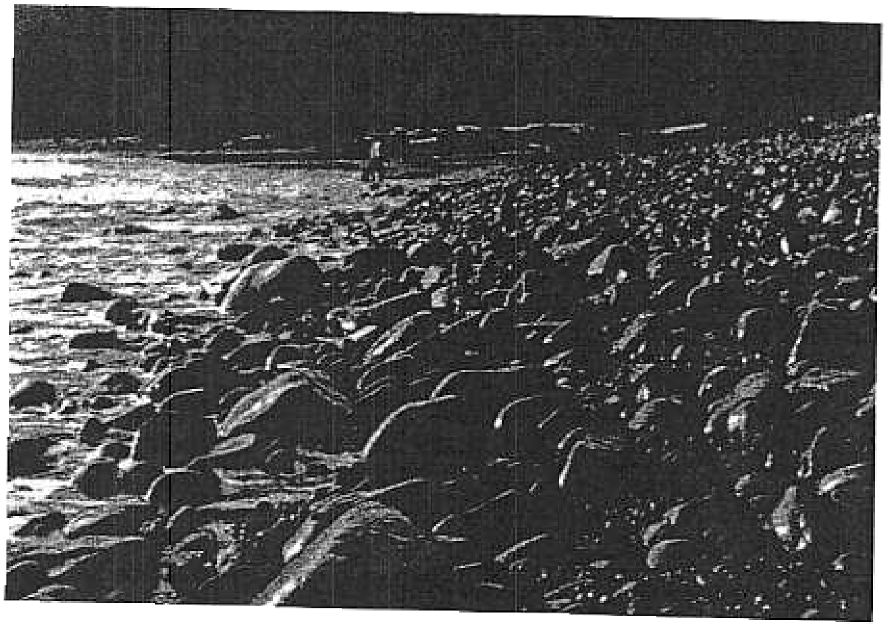
To summarize, the effect of waves approaching an irregular coastline is the formation of circulation patterns related to the direction of wave approach and the shape of the coastline. Water is pushed onshore by the waves and flows offshore as rip currents. Littoral currents occur within the surf zone and move from areas of relatively high energy (headlands) to low energy (embayments).

Nearshore Sediment Transport. The nearshore circulation system is very effective in moving sand. Waves provide the energy to erode the coastline and temporarily suspend sedimentary particles, while the longshore currents transport the sediment along the coast. The process of suspension and movement of sediment in the surf zone is called *longshore*, or *littoral*, *drift*. Laboratory and field studies have shown empirically that the sand transported as littoral drift can be related to the wave energy expended on the beach.

Moving water transports sand according to its *competency*, or the

Figure 10-7
Schematic diagram of the nearshore circulation pattern on a straight beach. (From F. P. Shepard, Submarine Geology, 2nd edition, Harper & Row, New York, 1963).

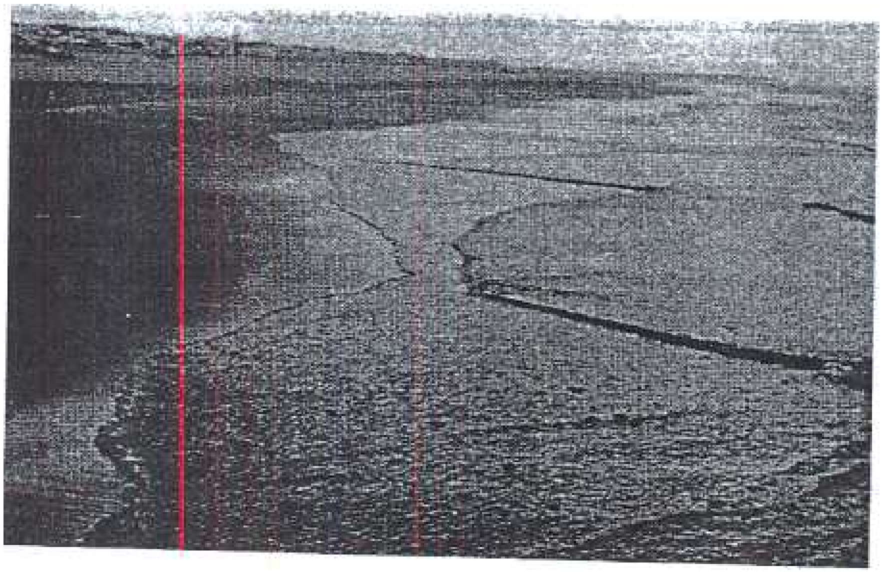




**A**

**Figure 10-8**
A steep rocky beach (A) and flat sandy beach (B) illustrate the association of beach slope with sediment size. (B courtesy of Clifford E. Moon).

**B**



size of materi
*capacity*, whi
moving. Wi
increase. He
littoral drift a

In gen
tudes or polar
bles, or cobbl
many tropical
are broad, ha
(Fig. 10-8B).
bayments, wa
the coast alo
(Fig. 10-9).

In the
with the swa
10-10 shows l
beach. This
drift but is h
of sediment n
the direction
pendicular to

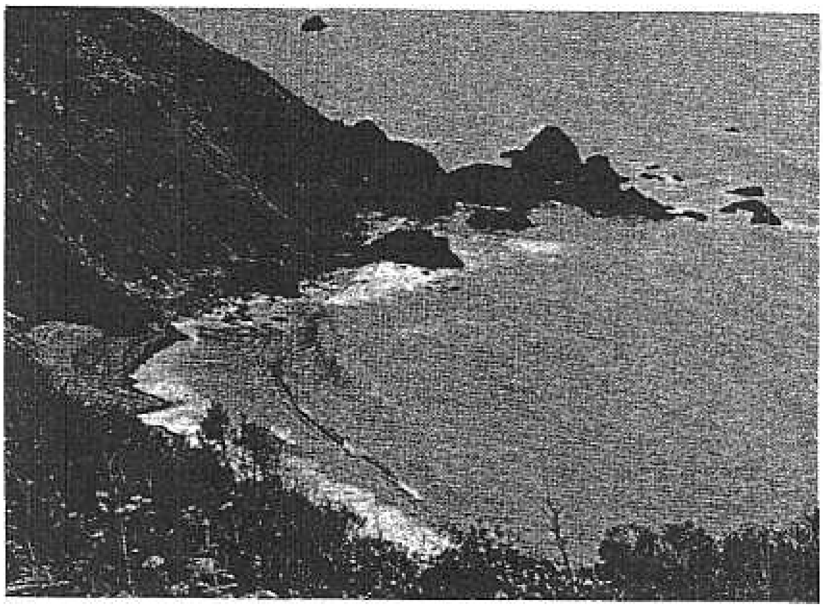


**Figure 10-9**
The sediment size in an embayment decreases from rocks on the exposed headland where wave energy is high to sand at the back of the bay where energy is low.

size of material that can be moved by a given current, and according to its *capacity*, which is the quantity of material that the flow is capable of moving. With increasing current speed, both competency and capacity increase. Hence, large waves are usually associated with higher rates of littoral drift and move coarser sediment than small waves do.

In general, beaches on stormy coasts (e.g., in high temperate latitudes or polar regions) are steep, narrow, and consist of coarse sand, pebbles, or cobbles (Fig. 10-8A). Protected beaches and those located in many tropical areas, where winds and waves have low energy, frequently are broad, have gentle slopes, and are composed of medium to fine sand (Fig. 10-8B). Similarly, around headlands, wave energy is high; in embayments, waves are smaller. Bays, therefore, have sandy beaches, whereas the coast along headlands is rocky or consists of quite coarse material (Fig. 10-9).

In the swash-backwash zone, sand is transported up the beach face with the swash and moves directly downslope during backwash. Figure 10-10 shows how this motion results in a net drifting of sand along the beach. This *beach drift* is generally parallel to the direction of longshore drift but is highly irregular. Note that the direction of these two modes of sediment movement is dependent upon the direction of wave attack. If the direction of wave attack is resolved into components parallel and perpendicular to the direction of the beach, the direction of the parallel com-

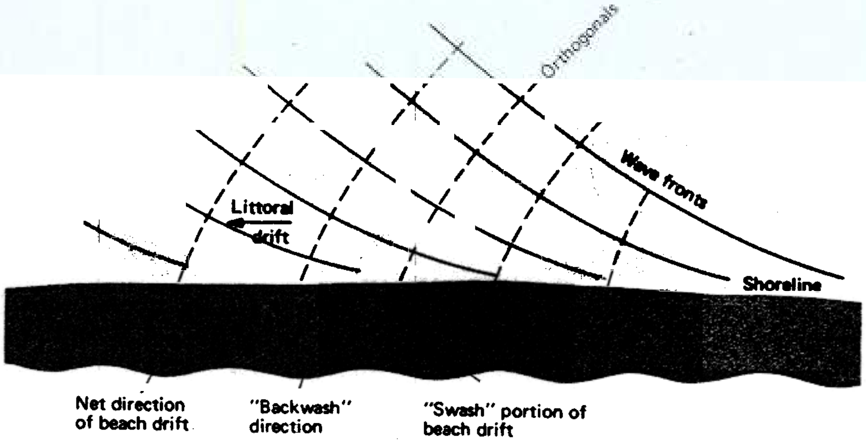


**Figure 10-10**
Sediment movement along the beach occurs in the surf zone as littoral drift and on the beach face as beach drift.

ponent indicates the direction of sediment drift (see Fig. 10-4), and its length indicates the relative strength of the current.

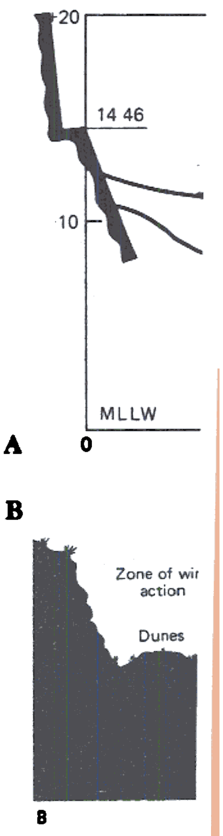
The two processes, beach drift and littoral drift, transport beach materials from river mouths and eroding headlands to their ultimate destination in embayments or, via submarine valleys and canyons that intercept littoral drift, to the sea floor lying below depths affected by wave activity.

The sands, gravels, and coarser materials on the beaches have formed gradually throughout geologic time. Indeed, some sands have existed as such for centuries. In other cases, sand has gone through several cycles of incorporation in sedimentary rocks (sandstones), erosion, transportation to the beach, and movement in the littoral zone. In a geological sense, involvement in such cycles is transitory, as are the beaches we enjoy today. Compared to the quantity of sand that has been made throughout geologic time, the amounts being introduced today are relatively small. Therefore, the net removal of sand to below the limit of wave activity must proceed at a relatively small rate; otherwise, the coasts along the world ocean would be barren rock cliffs and wave-cut platforms except near the mouths of large rivers.

**The Beach Profile.** Direct observations of beaches establish that sand transport in the littoral zone is primarily along the shore. Where prevailing winds and semipermanent storm centers cause waves to attack the coast chiefly from one direction, there is a natural tendency for the beach to adjust itself to the average waves and the rate of sediment supply. The distribution of wave energy will cause the beach either to *prograde* (build out) locally or to recede so that a dynamic equilibrium is eventually attained. This equilibrium often reflects some sort of annual average wave condition. However, the sediment in a sector can vary from being eroded

in winter to beir
waves changes
changes through
grading, whereas
Laborato
period, steep wa
an increased cap
ditions, sand is
the seaward par
attacked by swe
from distant sto
distances offsho
erosion of the p
beach face, rela
narrow shelf).
less steep beach

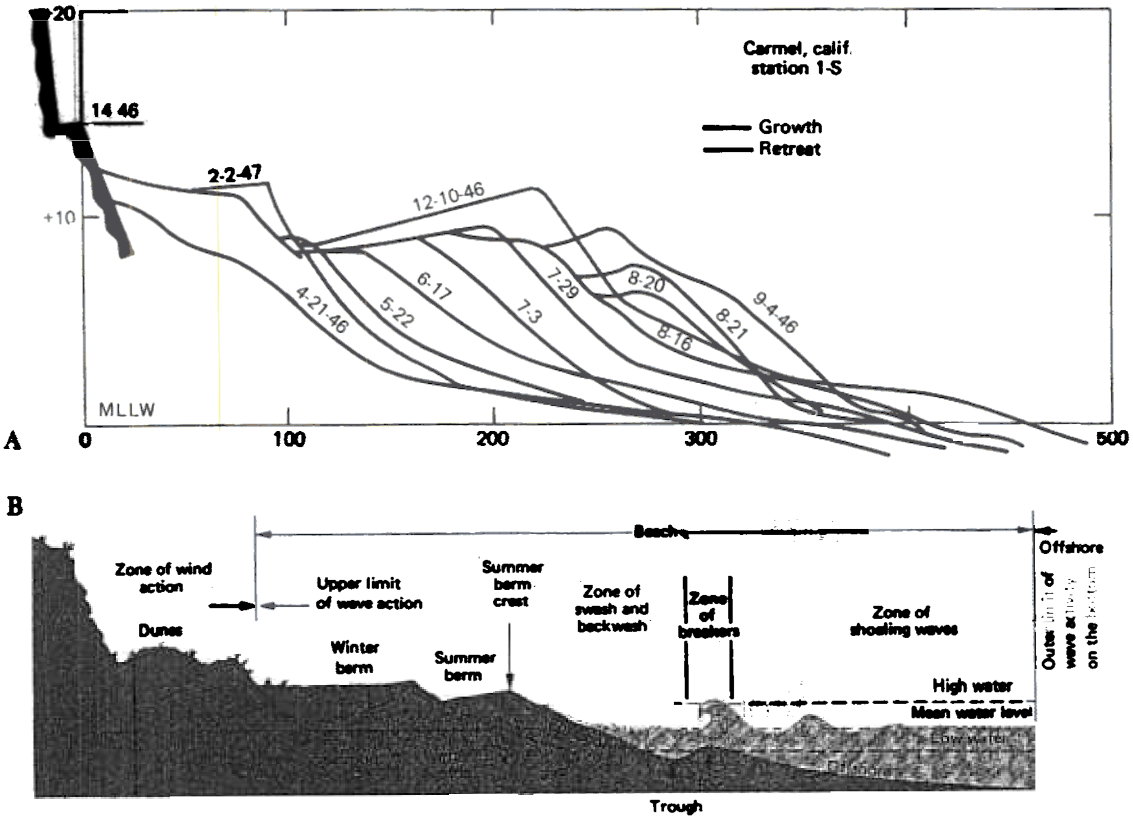
The beach
condit
(A after



in winter to being prograded during the summer, because the nature of the waves changes seasonally. Figure 10-11A shows a beach profile as it changes throughout the year. From April to September, the beach is prograding, whereas it retreats during the winter season (September to March).

Laboratory studies and measurements on beaches show that short-period, steep waves from local winter storms occurring close to shore have an increased capacity and tend to keep sand suspended. Under these conditions, sand is removed from the beach by rip currents and deposited in the seaward part of the littoral zone. During the summer, the beach is attacked by swells with long wavelengths and low steepness that arrive from distant storms. These waves influence the floor of the sea at great distances offshore and gradually return sand shoreward to repair the beach erosion of the previous winter. A winter profile is recognizable by a steep beach face, relatively coarse sediment, and a sea cliff or winter berm (a narrow shelf). A summer beach profile is characterized by finer sediments, less steep beach face, and smaller berm. Sometimes certain portions of

**FIGURE 10-11**
The beach configuration changes throughout the year as a function of wave conditions (A). The characteristic elements of a beach profile (B). (A after Office of Naval Research, 1957; B after A. N. Strahler, 1963).



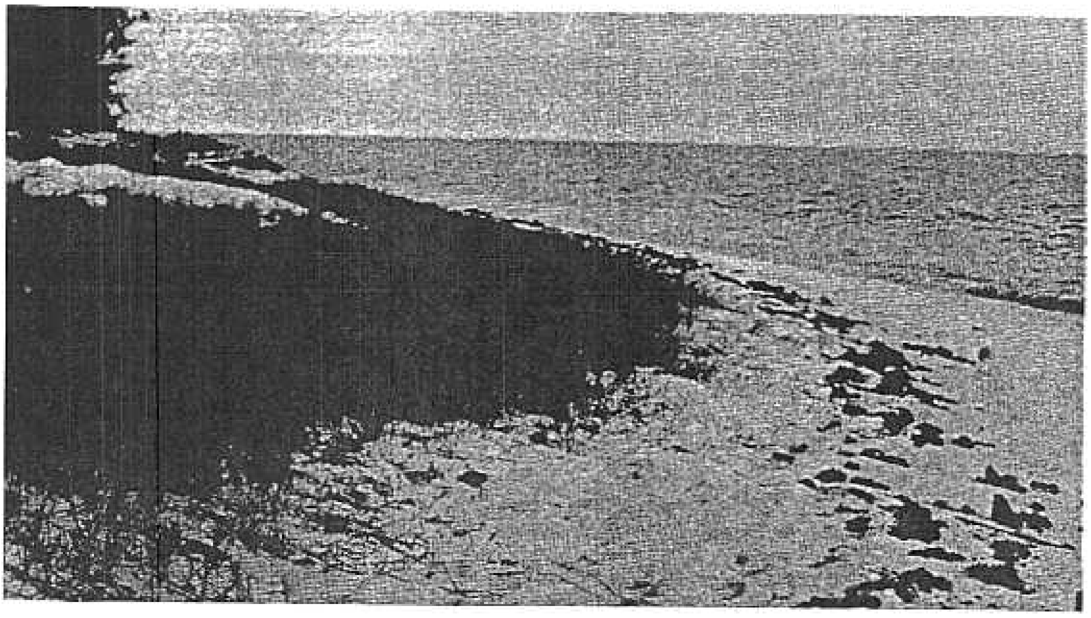
the winter profile (i.e., the winter berm or some offshore bars) remain as remnant features because of the inability of the summer waves to affect them (Fig. 10-11B).

We can often determine the state of the sediment and the short-term processes acting on a beach sector by examining certain features of a beach. Its configuration in profile and plan, distribution by grain size of beach sediments, and types of vegetation at the shore indicate whether a beach is being eroded or accreted.

In addition, a beach's features reveal the types of waves acting on it. The slope of the beach and the height of the berm are determined by the energy in the swash of the waves. An energetic swash will carry sand to the top of the beach berm and deposit it there, thus steepening the face of the beach. If the energy of the waves increases suddenly, a sea cliff quickly forms because of the increased rate of erosion. Under prolonged attack, however, a smooth slope eventually results. If waves are so energetic that the swash overtops the berm, the beach will build upward in response. If this action occurs infrequently, coastal winds may erode the berm and build a dune field behind the beach. When conditions remain relatively constant for several years, certain types of vegetation, crawling plants, and beach grasses (Fig. 10-12) will become established and stabilize the beach in that configuration.

The distribution of various types of sand on a beach reflect the prevailing regimen of waves. Extremely coarse and heavy materials tend to

Figure 10-12
Grasses growing on the beach face help to stabilize the sand and promote further deposition.



Sedimenta
by wave ac
and density,
bands p
Examples o
bands of shel
layering
minerals (B).
(B) are ap

remain wher
berm. Extre
and so are re
normal wave
present in m
remain after
and stringers
zones of con

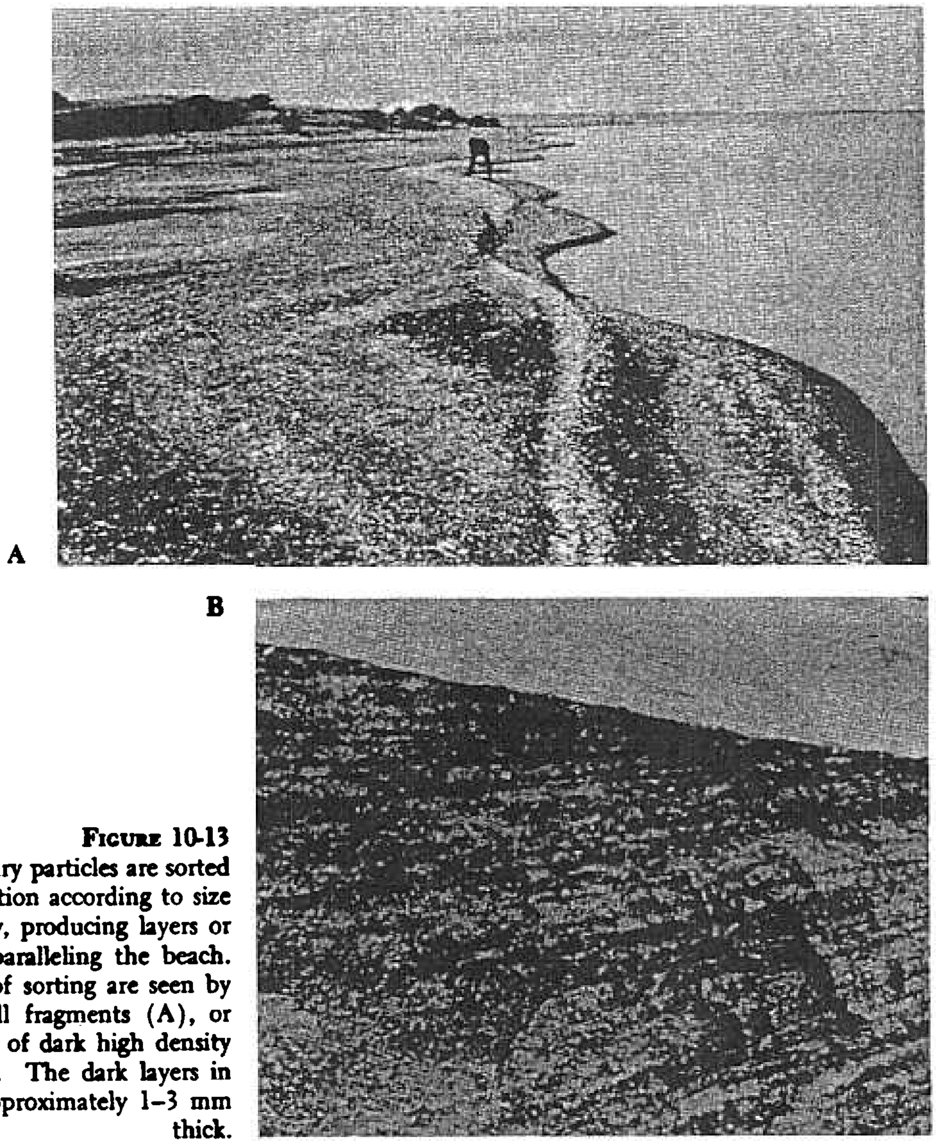


**Figure 10-13**
Sedimentary particles are sorted by wave action according to size and density, producing layers or bands paralleling the beach. Examples of sorting are seen by bands of shell fragments (A), or layering of dark high density minerals (B). The dark layers in (B) are approximately 1–3 mm thick.

remain where the strongest waves deposit them, usually along the highest berm. Extremely fine and light materials tend to persist in suspension and so are removed downcoast and eventually seaward. Variations in the normal wave patterns are shown vividly where dark, heavy minerals are present in minor quantities in a light-colored sand. The heavy minerals remain after the differential erosion of the light sand; in this way, lenses and stringers of heavy materials become segregated. Sometimes layers or zones of concentrated shell fragments are separated by the same process

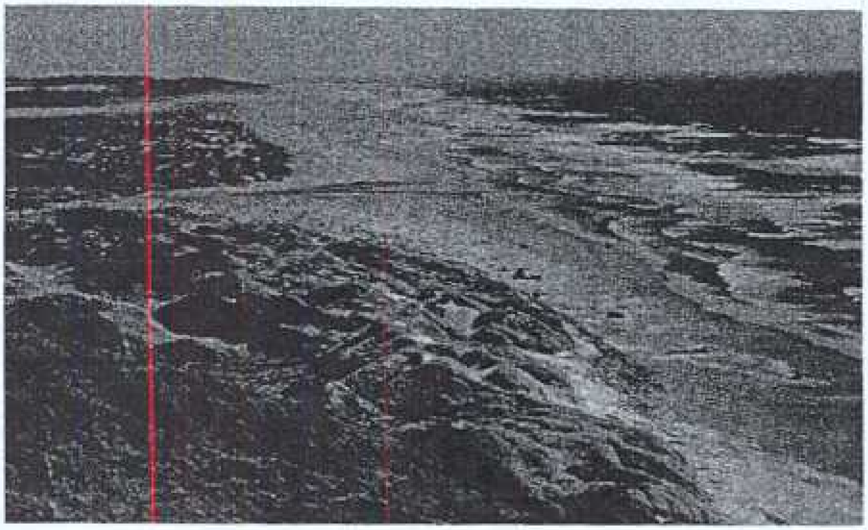


Figure 10-14
Coastal sand dunes represent a depository of excess beach sand.

(Fig. 10-13). These layers often are exposed in sea cliffs that form when steeper waves begin to attack the shore.

Nearshore Deposition and Erosion. Scientists do not completely understand how sand movement onshore and offshore responds to wave conditions. Much of what we know about this complex mechanism comes from studies of beach models in wave tanks where scaled experiments are conducted. Although natural beaches do not always corroborate observations of beach behavior in models, at least some broad generalizations can be drawn. Empirical measurements on natural beaches are generally not satisfactory, because the generalizations derived usually apply only to a single location.

The movement of sand along the coast is the result of many individual littoral drifts acting on discrete coastal segments. Locally, the currents move sand from promontories toward embayments. Regionally, the drift tendency is in the direction of the longshore component due to the prevailing wind waves. Most littoral sand is introduced at the mouths of streams. Sand is lost as it is carried by steep, high waves into deep water or submarine canyons, or as it is removed to dunes by onshore winds (if rainfall is not excessive) as seen in Fig. 10-14. The long-term effect of all these factors is a straightening of an irregular coastline.

Whenever either a longshore current is interrupted or the waves that provide the energy to maintain the longshore current are interrupted, the capacity of that flow to transport sediment is decreased and deposition occurs. Figure 10-15 shows how an embayment interrupting a straight

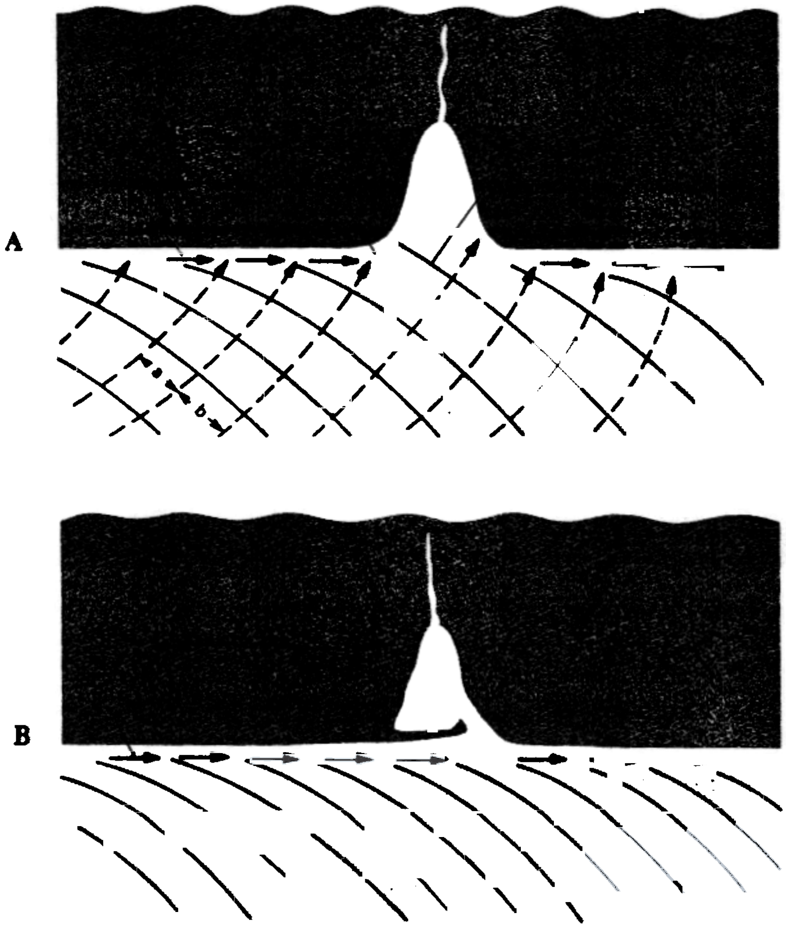
---

coast alters the
drift occurs, ca
the mouth of t
vigorously flowi
pletely sealed.
fluctuation in t
littoral drift an
Often the way
sediment drift t
years. If we ex
of the prevailin
Frequen

coast alters the wave refraction in such a way that deposition of littoral drift occurs, causing the formation of a spit or small point of sand across the mouth of the bay (Fig. 10-16). In cases where the embayment has a vigorously flowing river at its head, the estuary will never become completely sealed. However, the river may be forced to migrate because of fluctuation in the dynamic equilibrium between sediment deposition from littoral drift and sediment erosion by outflowing river water (Fig. 10-17). Often the way in which a spit has been built indicates the direction of sediment drift that has persisted in that area for a considerable number of years. If we extend this reasoning, we can sometimes infer the direction of the prevailing winds or waves.

Frequently, the natural tendency of littoral processes is not de-

**Figure 10-15**
Formation of a spit across an estuary. The spit builds into the estuary because of wave refraction into the mouth of the bay. (A) initial situation; (B) well-developed spit.



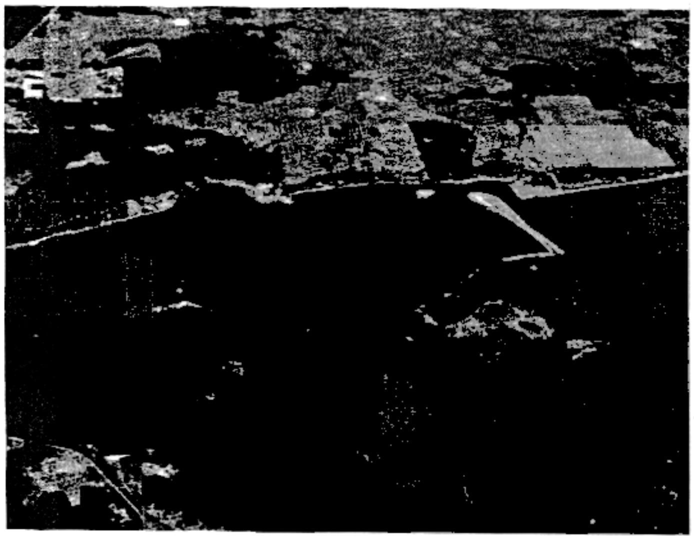


**Figure 10-16**
The straight narrow spit forming this tidal embayment was built by longshore drift moving from right to left. (Photograph courtesy of Dennis Byrne).

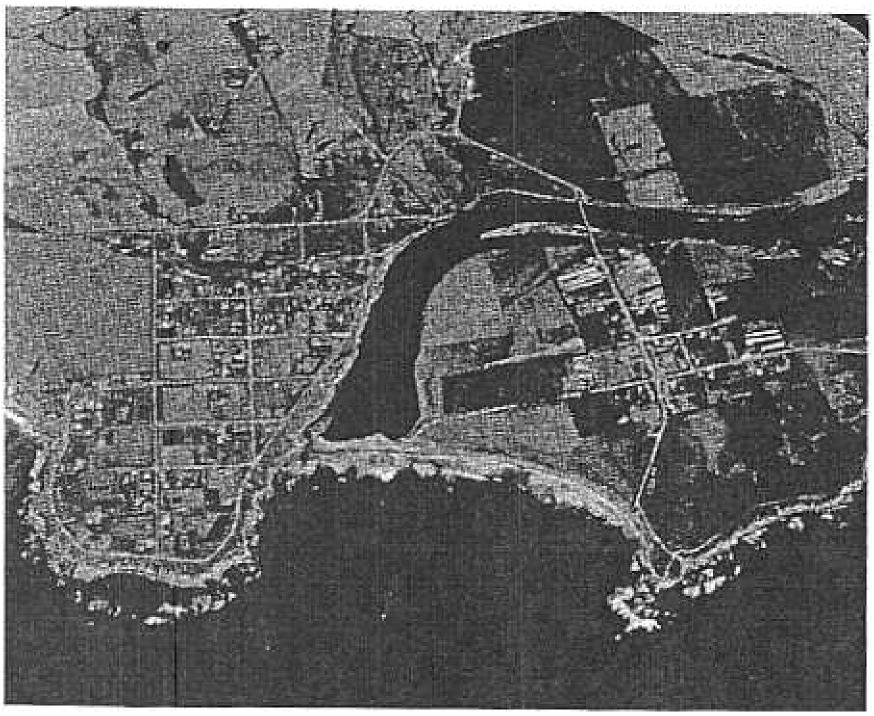
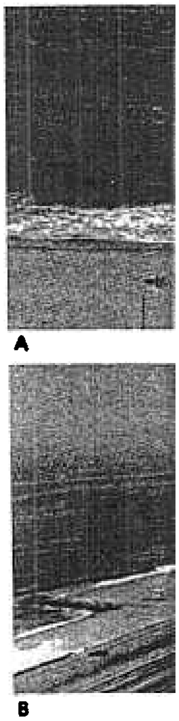


**Figure 10-17**
Due to longshore drift a spit has been built across a river mouth. Note how the river has been forced to erode the opposite bank as a result of spit growth. (Photograph courtesy of Peter B. Taylor).



Photograpl
around a s

sirable. Coas
where they ar
wide variatior
years. Somet
sudden chang
is desirable tc
tion. In oth
erosion of be
prolonged pe
Techn
retarding the
from the hea
protect segme
ing in sand tc
Figure
sediment drif
from the bea
must extend
groin is instal

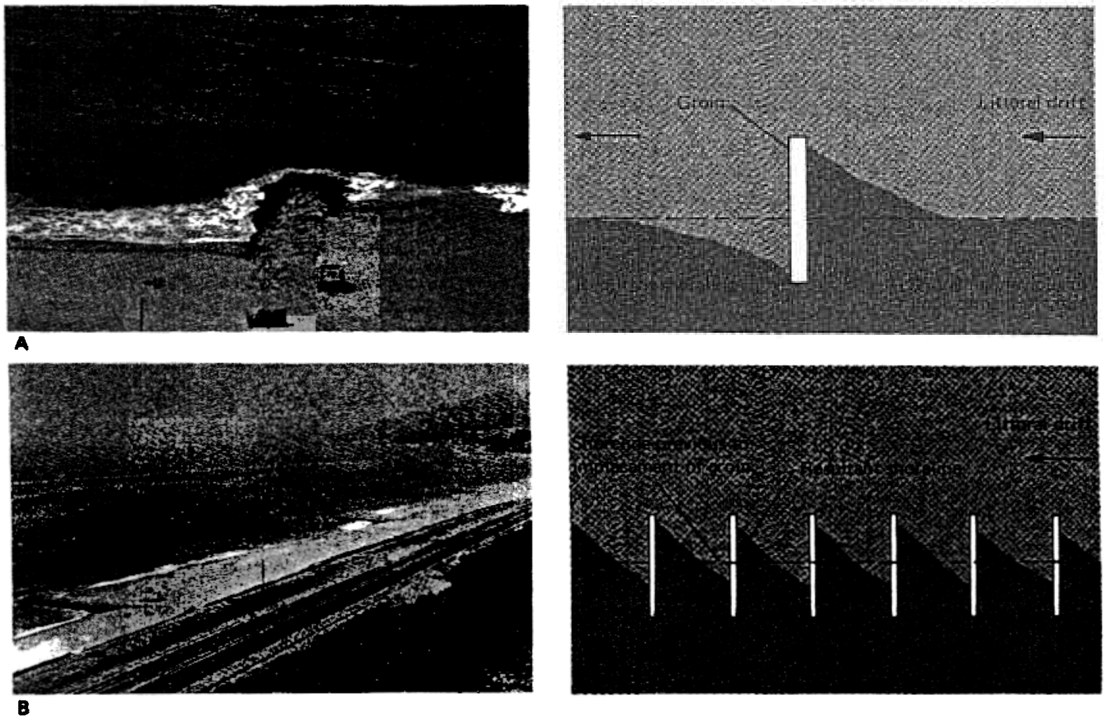


**Figure 10-18**
Photograph and line drawing of (A) nearshore refraction and sedimentation around a single groin; (B) sedimentation associated with a series of groins.

sirable. Coastal installations are jeopardized if excessive erosion occurs where they are built or if they are built on an unstable beach, in which wide variations in accretion and erosion take place yearly or over a few years. Sometimes a man-made interruption of littoral drift precipitates sudden changes in the configuration of the coastline. In all these cases, it is desirable to stabilize the beach and prevent excessive erosion or accretion. In other words, littoral drift must be stabilized. In practice, it is erosion of beaches that must be controlled, for losses of sand during a prolonged period of erosion tend to be permanent losses.

Techniques for controlling beach erosion involve such procedures as retarding the littoral drift rate, trapping sand or otherwise diverting sand from the heads of submarine canyons, building jetties and breakwaters to protect segments of beach exposed to concentrated wave attack, or bringing in sand to nourish eroding beaches.

Figure 10-18A illustrates the effects of a deliberate interruption of sediment drift. This figure shows a groin, or barrier, constructed to extend from the beach out into the breaker zone. To be effective, this groin must extend from the bottom of the surf zone to high-tide level. When a groin is installed, it dams the littoral drift. Thus, sand accumulates as sedimentation on its updrift side; subsequently, sand is removed (erosion) on its downdrift side. Figure 10-18B shows the effect of a series of groins constructed to increase the area of a sand beach.

Deposition of littoral drift also occurs when the waves that provide the energy to move sand are interrupted. A simple breakwater parallel to shore may decrease wave surge in a harbor entrance, but it also causes sand deposition as shown in Fig. 10-19. Some other examples of common breakwater configurations are also shown. Note that both a zone of accretion and a zone of erosion are associated with the breakwater. Generally, sand is dredged or pumped from the site of deposition to the zone of erosion. Although the cost is considerable, this procedure maintains the harbor entrance and minimizes damage by erosion.

## FLUCTUATIONS IN SEA LEVEL

Sea-level changes have a considerable influence on coastal processes and on beaches. A large tidal range is often associated with broad beaches and extensive salt marshes. Wave energy is greatly diminished by friction over the broad intertidal platform, and coastal erosion is intermittent. The strength of tidal currents is associated with tidal range. In coastal areas exposed to both large waves and a large tidal range, erosive processes can be significant in the nearshore zone.

Changes in sea level have occurred in past geologic time as a result of vertical movements of the land and changes in the volume of water in the ocean basins. The land can move either up or down and submerge or raise coastal areas. Such movements can be related to faulting, folding, and tilting of the earth or to isostatic adjustments of the crust when heavy loads of ice, sediment, or lava are added or removed. For example, crustal subsidence generally occurs in the vicinity of large deltas; crustal rebound follows a period of glaciation.

Coasts that have been influenced by recent earth movements are recognized in New Zealand, New Guinea, Japan, California, and around the Mediterranean Sea. Isostatic movements from the melting of continental glaciers are recognized in Scandinavia and Canada.

The continental glaciers of the Pleistocene epoch removed significant volumes of water from the ocean basins. Geological evidence from the land has led scientists to conclude that the Pleistocene epoch was characterized by alternate advances and retreats of the ice of continental glaciers. Sea-level fluctuations accompanied these oscillations in ice formation.

Calculations of the volume of water frozen in glaciers during the last glacial stage indicate that the sea level must have been lowered by 110 to 130 m. These calculations are corroborated by fathograms of submerged shorelines and by beach sands dredged from depths to 130 m throughout the world.

The ice of the last glacial stage began to melt about 20,000 years

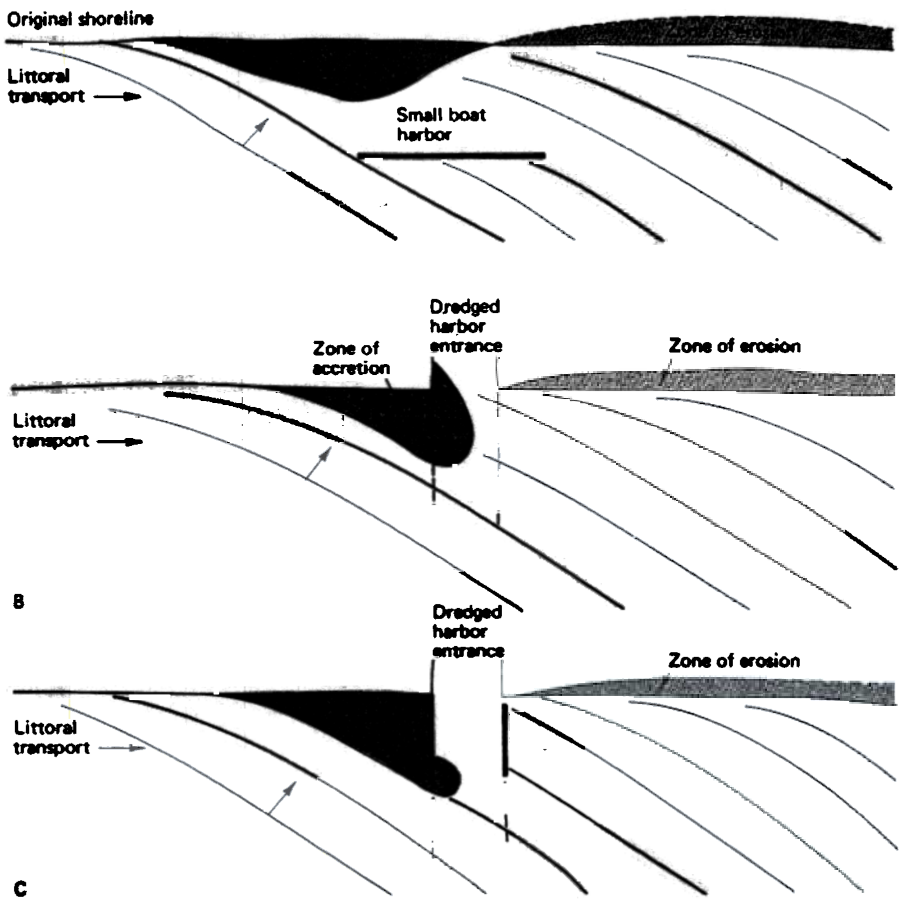


FIGURE 10-19
Deposition of sediment associated with the interruption of longshore currents in the nearshore zone.

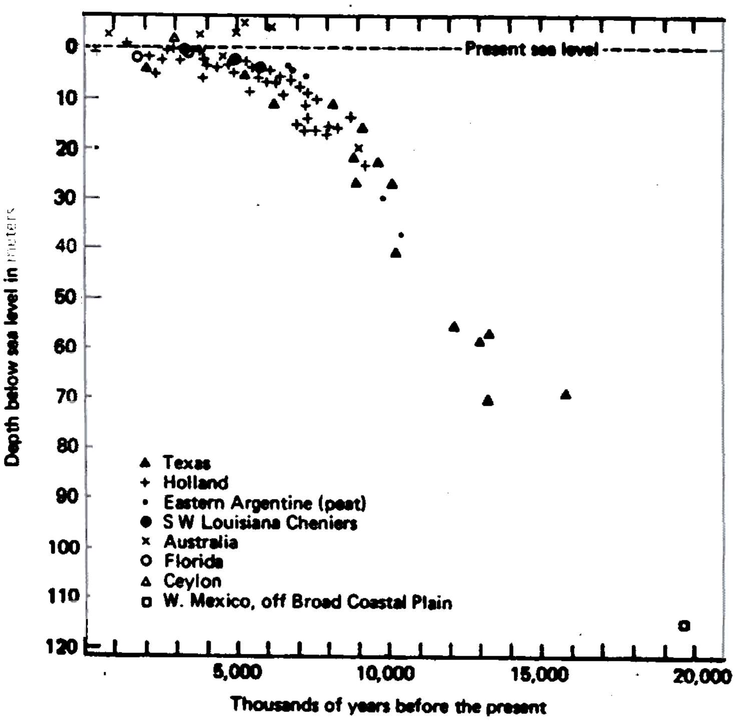


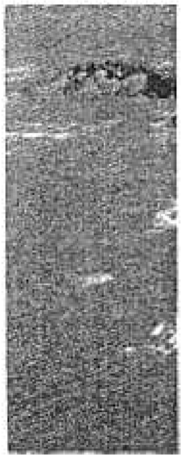
**Figure 10-20**
Estimates of the Holocene marine transgression during the past 20,000 years. (Permission of F. P. Shepard).

ago. Since then, the sea level has risen approximately 120 meters (Fig. 10-20). All of the estuaries, embayments, and coastal regions of the world have also been inundated by the Holocene marine transgression of the past 20,000 years. Most coastal features represent effects of erosion, deposition, and biological growth that have occurred in the past few thousand years.

## GEOLOGIC INFLUENCE

The degree of erosion in a coastal zone depends on the differences in hardness and durability of rocks. Variations in the character or structure of coastal rocks exposed to waves and seawater thus are accentuated by differential physical or chemical erosion.

The resistance of a rock can be measured by (1) its hardness or ability to withstand constant wave attack, (2) its chemical resistance to the solvent properties of seawater, and (3) its ability to undergo processes of continuous wetting and drying. On exposed coasts where wave forces are great, the harder rocks stand as rocky promontories after the softer ones have been removed (Fig. 10-21), or they form bold cliffs surrounded by shore platforms. The durability of rocks exposed to identical oceanic conditions can be compared in Figs. 10-22 and 10-23.



Numerous
evidence of
coast du

When rock i
durable, cliff er
slowly. Here
planes of the la
orientation of