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Shoreline Processes*

John H. Hoyt, University of Georgia

COUNCIL ON EDUCATION IN THE GEOLOGICAL SCIENCES

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John H. Hoyt[1]
University of Georgia

INTRODUCTION

The concept of uniformitarianism suggests that the shoreline processes of today are much the same as those in the geologic past. Waves, driven by the wind, relentlessly attack the shore. To protect itself from the sea, the land girds itself with the soldiers of its command: the sands and gravels of the beach. The greater the force of the attacking sea, the greater the need for defending soldiers, but, as in any battle, strength is limited by the material available.

So what has been learned in recent years to help us to understand what goes on along the shore? In truth, it is mainly details, but they promise to help us if only to point the way for further study. What follows places in perspective the principles and observations that seem most relevant to shoreline processes as they relate to sea level, deltas (see also Morgan, 1970), inlet migration, surf-base, and storms.

SEA LEVEL

Because shoreline processes are tied to the position of the sea, it is not surprising that changes in sea level are very important in shaping coastal features. Our realization that in many areas of the world sea level is near maximum altitude for the Holocene epoch (Shepard and Curray, 1967; Scholl *et al.*, 1969), rising at a rate of nearly one half foot per 100 years since the turn of the century (Donn and Shaw, 1963), has helped to explain many of the anomalies in shore stability apparent in many areas.

It is evident that a rise in sea level will allow the sea to inundate additional land area; less evident is the readjustment of the beach and nearshore profile which accompanies this rise (Brunn, 1962; Schwartz, 1967). Figure 1 illustrates the transfer of sediment which accompanies a rise in sea level and the resulting large advance of the sea. This phenomenon helps to explain the rapid rate of erosion occurring along many of the coasts of the world.

Man's eagerness to place resort facilities and dwellings as close to the shore as possible has resulted in the destruction of many dune accumulations which had provided a buffer zone to retard shore erosion. The net effects of the rise in sea level and man's foolhardiness have been accelerated erosion at the most critical locations, and the need for restoration of beaches which is costly and commonly ineffective.

Sea level has been rising for the past 15,000 to 18,000 years as a consequence of the melting of the Wisconsin continental glaciers. It is unlikely that this was a simple continuous rise, but details are difficult to document (Fairbridge, 1961; Curray, 1965). The past few thousand years should furnish the clearest record, but even during this

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CEGS
American Geological Institute
2201 M Street, N.W.
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[1]Contribution No. 198, Marine Institute of the University of Georgia.

This review is published posthumously, essentially as received from Dr. Hoyt prior to his fatal glider accident 6 September 1970. The editors have incorporated the suggestions of the reviewers which increase clarity but have made no substantive changes that would alter the scope or format intended by the author. Although the review emphasizes major shoreline processes, largely in an historic context, and omits extensive discussion of beaches, tidal flats, and several aspects of deltas, we believe the presentation is a useful synthesis and should be published, both on its own merits and as a tribute to Dr. Hoyt.

interval sea movements have occurred apparently at different rates and even in different directions at various coastal locations. Thus, shoreline and nearshore processes have been operating on a comparatively inconstant framework, and only during the past 4,000 years or so has there been sufficient stability to permit the development, in some areas, of an equilibrium profile in the nearshore area.

The characteristic shallow-water profile, steep near the shoreline and more gently sloping offshore, is achieved in different ways in different areas, depending on the initial morphology of the particular area. Along coastal plains, which commonly are characterized by gently sloping shelves, the equilibrium profile is produced by the transfer of material from a few miles offshore to the shoreline, resulting in a deepening of the offshore area and a progradation of the shore. The amount of material moved depends on the initial slope, wave size, tidal range, grain size, and other factors. Because wave motion is directed toward the shore, sediment will move shoreward until a balance is achieved between the inward forces and the seaward component of gravity. There is a different equilibrium point for each grain size with the coarsest material concentrated inshore in the highest wave energy area where the slope is greatest (Johnson and Eagleson, 1966). Thus, the equilibrium profile and the increasingly finer sediment offshore are results of the same processes. The comparatively brief period of time since sea level attained its present position and the lack of sufficient sediment to blanket the shelf completely have restricted the grading process to the shore face and the inner part of the shelf in many areas.

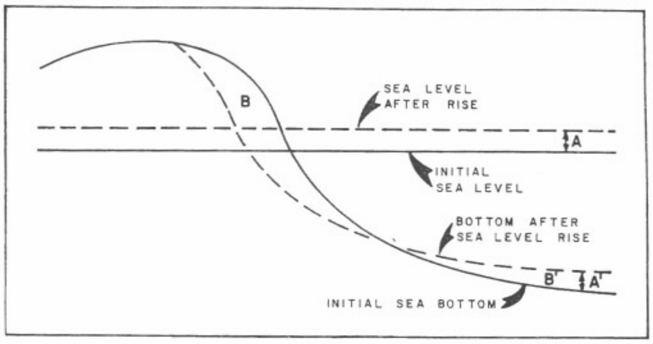

Figure 1. Shore erosion following a rise in sea level. Sediment eroded from beach and dunes, B, is deposited in nearshore area B1. After Schwartz, 1967.

The recognition of the importance of submergence as an influence on shoreline processes has required the reinterpretation of some existing theories of shoreline sedimentation. Detailed studies along several barrier island coasts (Fisk, 1959; Rusnak, 1960; Bernard *et al.,* 1962; Hoyt, *et al.,* 1964; Van Straaten, 1965; Hoyt and Hails, 1967) suggest that the theory of the formation of barrier islands from offshore bars, as summarized by Johnson (1919), needs revision. Development of islands from bars implies the existence of open marine conditions shoreward of the bar; appropriate sediments, fauna, and morphology should be found along the pre-island shoreline (Figure 2). The apparent absence of these elements landward of the barriers in these detailed studies indicates other methods of formation must be considered.

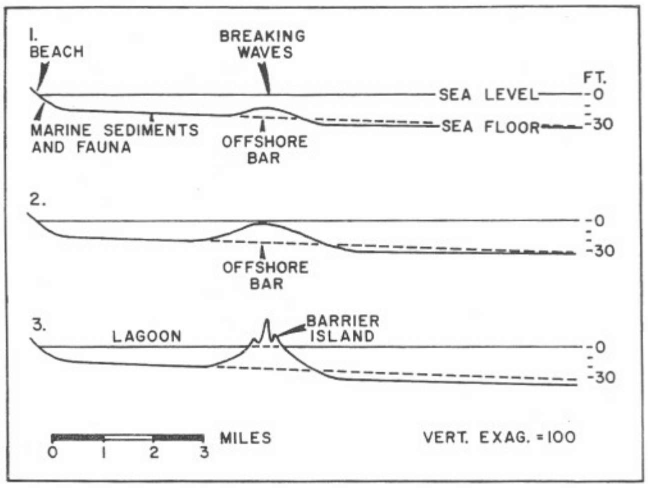

Figure 2. Idealized cross sections showing barrier island formation from an offshore bar. (1) Waves agitate sea floor and deposit sediment to form bar in area of energy loss. (2) Sediment accumulates to near sea level. (3) Bar is converted to island with lagoon on landward side. Note open marine sediments, fauna, and morphology, landward of bar before bar becomes island. From Hoyt, 1967a.

As an alternative, it has been suggested that the development of an equilibrium profile along gently shelving coastal plains would supply sufficient sediment for the construction of beach/dune ridges along the shoreline which, with subsequent slow submergence, form the nuclei of barrier islands (Figure 3). The flooded area landward of the barriers becomes a lagoon; once formed, the barriers and lagoons are subjected to the modifications common to shoreline deposits. Because many of the original ridges were probably small, it is likely that the site of formation may not correspond with the present location of the islands. The narrowness of many barrier systems indicates that appreciable erosion and landward retreat of the barrier islands have occurred. In a few areas, where sediments were abundant and progradation has continued since the formation of the islands, the

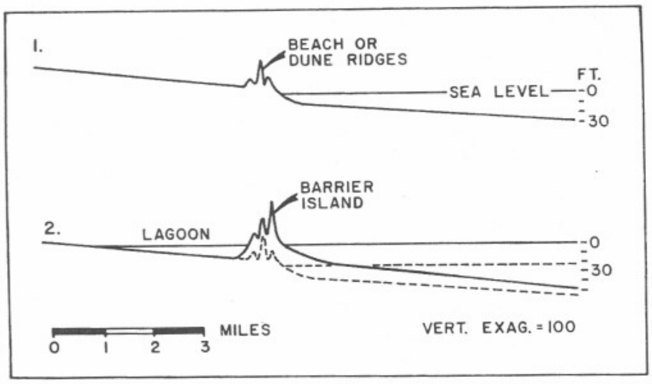

Figure 3. Formation of barrier islands by submergence. (1) Beach or dune ridge forms adjacent to shoreline. (2) Submergence floods area landward of ridge to form barrier island and lagoon. From Hoyt, 1967a.

initial barriers may be buried beneath lagoonal or salt marsh sediments, or they may have formed a platform upon which the present barriers have developed.

An additional complication in the barrier island development is the role of spits in barrier elongation and progradation. It should also be recognized that in certain favorable situations, such as prominent headlands or deltas, spits may form and, if subsequently breached, form barrier islands (Hoyt, 1967a). In other areas, retreating barriers may intersect the mainland and thus appear to have formed as spits. In any case, although methods of barrier island formation must be classed as hypotheses, the new evidence indicates the offshore bar theory is inadequate as a general explanation.

The problem of vertical coastal movements and their effects on shoreline processes have been considered for many years; tectonic displacement along the California coast and glacial rebound in the northeastern United States and Canada and in the Great Lakes and Baltic regions are classic examples. Somewhat less expected, however, is the influence of water loading of the continental shelf adjacent to the shoreline. Studies by Crittenden (1963) on former shorelines of Pleistocene Lake Bonneville in Utah led to similar computations along the northeastern United States coast by Bloom (1967). These studies indicate that the downward adjustment of the earth's surface for the load of water imposed on the continental shelf by submergence should be approximately one-third the effective water depth. The area of compensation may extend as much as 30 miles away from the location of applied load. Near the shore, because of shallow water depths, the displacement would be small; however, for areas with deep water nearshore, there could be an appreciable lowering of the land surface. The precise effect on the coastal area is complicated by such factors as the response time of crustal and subcrustal materials, the rate and amount of sea level rise, the dimensions of the area affected, and offshore water depth and profile.

DELTAS

An important aspect of shoreline sedimentation and processes is the introduction of large quantities of sediment at the mouths of major rivers. The nature of deltaic deposits is determined by many factors, such as type and quantity of sediment, river flow, distribution pattern, wave height, tidal range, and sea floor gradient. Shoreline processes common to open ocean coasts with high energy wave action may be considerably modified in the vicinity of large deltas. If the river waters carry much fine-grained sediment, the resulting high turbidity of the coastal waters can reduce appreciably the ability of the waves to sort and transport nearshore and littoral sedimentary accumulations. The reduced wave activity is commonly accentuated by shallow water depths nearshore. These effects, combined with a large supply of sediment from the river, may overwhelm the nearshore and shoreline distributive processes and result in the deposition of silts and clays in the littoral and sub-littoral areas. Such accumulations are anomalous along exposed, high energy coasts.

The delta building processes cause frequent changes in the location of river discharge into the marine environment. The proximity of sediment source greatly influences the sediment characteristics in depositional sites along the coast down drift from the delta. During periods when the river mouth is near a particular coastal area, there is rapid accumulation of relatively unsorted clay, silt, and sand (Byrne *et al.*, 1959). A shift in the discharge to a location farther removed from this depositional area allows reworking and sorting of the littoral and sub-littoral sediments and the formation of sand beaches and beach/dune ridge complexes. This sequence of sedimentation results in the formation of cheniers and chenier plains which are characteristically associated with some major deltas (Figure 4) (Price, 1955).

Another characteristic of deltas is the localized or regional subsidence of the coast caused mainly by the weight of the sediment being introduced. As additional sediment is deposited, that part of the delta progrades, but a subsequent shift in the depocenter, combined with compaction of the sediments, may result in submergence of the original depositional area. During submergence, waves will rework the distal part of the abandoned delta forming beaches and beach/dune ridges. With additional submergence, the part of the delta landward of the ridges will be flooded to form a lagoon and the ridges will become barrier islands. The Chandeleur Islands and Chandeleur Sound on the east side of the Mississippi delta appear to be results of this process.

INLET MIGRATION

An important process along many shorelines, particularly those of coastal plains, is the lateral shifting of inlets in response to longshore currents. Most coastal areas have a dominant direction of littoral and sub-littoral drift which is commonly dictated by wind direction in relation to shore trend. The longshore currents transport sediment to the upcurrent side of an inlet where the combination of deeper water and reduced wave activity favors deposition. Over a period of time, a significant accumulation of sediment on one side of the inlet is accompanied by erosion on the other side, and the inlet migrates in a down current direction. In areas where there are a number of inlets, a significant part of the coastal sediments may accumulate in the inlet environment. In modern deposits, the importance of shifting inlets has been limited by the comparatively brief

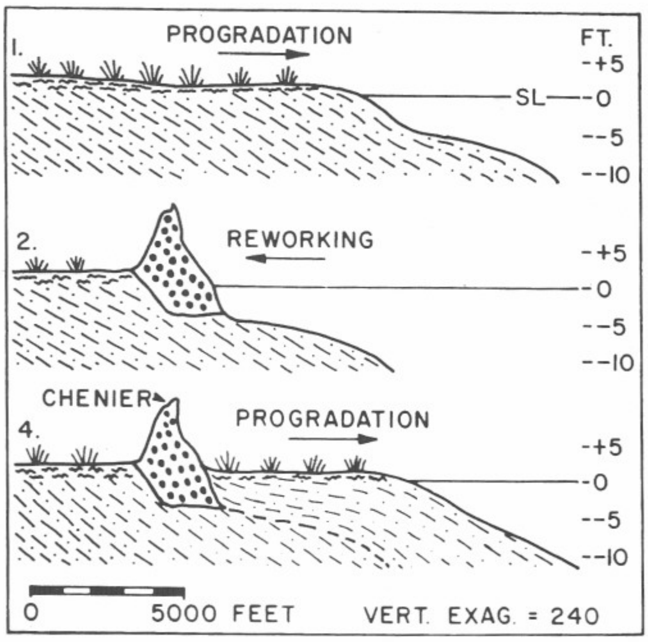

Figure 4. Idealized cross sections showing development of chenier. (1) Mudflat progradation. (2) Erosion and reworking of mudflat deposits and formation of ridge along shoreline. (3) Mudflat progradation, ridge becomes chenier. SL = sea level. From Hoyt, 1969.

time sea level has been near its present position; however, in ancient deposits where geologic time precludes such limitations, inlets probably played a much more significant role.

Because many shoreline sediments accumulate in the inlets, it is important to understand the characteristics of this environment. One important consideration is the relative depth of the inlet compared with nearshore areas in the same locality. Although there are variations in areas around the world, the inlet generally has a greater depth than other nearby environments. Along the Georgia coast, for example, inlets are 60 to 80 feet deep, but comparable depths are not encountered closer than 25 miles offshore (Hoyt and Henry, 1967). Another important factor is the bidirectional flow characteristic of inlets which are usually oriented perpendicular to the flow associated with longshore currents. The landward-seaward currents, which may flow at speeds as high as a few knots, commonly produce ripple marks in a variety of sizes up to sand wave size with amplitudes of several feet and wave lengths of several hundred feet (Figure 5). The steep slope of the asymmetrical ripples may be directed toward

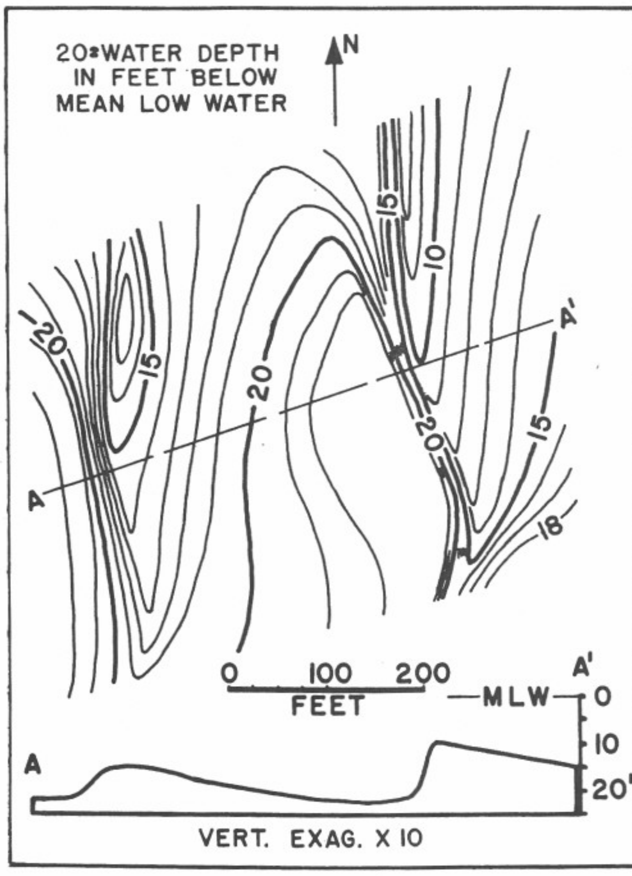

Figure 5. Contour map and cross section of sand waters in channel inlet. Cross section at bottom of figure perpendicular to sand waves. From Hoyt, 1967b.

the land or toward the sea. Also, because deposition occurs on the sides of the inlet, there is often a component of stratification dip toward the channel in the direction of channel shifting; however, this angle of inclination is generally small compared to the steep dip associated with ripples.

Along inlets, there are ordinarily alternations of sediment type from gravel to clay. The sediment deposited, of course, depends on what types are available, but in areas where a variety of sizes are present, gravel and coarse sand are accompanied by lenses of clay and fine sand. This variation in sediment type reflects the rapid changes in the sedimentary conditions in the inlet environment and may represent ripples in which coarse sediment shifted over the finer material already accumulated in the trough on the lee side of the ripple. Coarse sands and gravels also commonly have a matrix of clay and silt sediment which may be introduced after deposition of the coarser particles by sub-bottom flow.

Inlet sedimentation processes are important because under some conditions of strong longshore drift, the sediments which accumulated near the shoreline may be largely replaced by sediments deposited in the inlet environment. In addition, the area affected by the inlet processes is quite large because the channel often extends several miles offshore. In considering the preservation of shoreline sediment in the ancient record, the inlet sediments have an additional significance. During transgression, the upper part of the shoreline sediments may be eroded and the record of the shoreline position destroyed (Fischer, 1961). The depth and extent of this erosion will vary with the particular conditions, but much of the littoral and sub-littoral sediments could be removed. The inlet sediments, because of their depth of burial, may be the only indication of previous shoreline positions.

SURF BASE

The concept of wave-base has been modified as a result of recent information (Dietz, 1963). For many years, it was assumed that the continental shelf was formed as a very large wave-cut and fill terrace, and that wave-base approximated the shelf edge. Although the effectiveness of storm waves in moving sediment on the continental shelf is still a subject for investigation, it has become apparent that effective wave-base as an erosional agent is much shallower than previously thought and probably averages about 30 feet in depth. To avoid confusion, this limit of marine abrasion is called surf-base although it extends seaward of the actual area of breaking waves, to the greatest depth where waves begin to build up appreciably during storms. Along with wave-base, the concept of wave-built terraces is suspect and true examples appear to be rare (Dietz, 1963). On the other hand, wave-cut terraces are common geomorphic forms but appear to be limited to the depth of surf-base.

STORMS

Considerable research has been done recently on the effects of storms on coastal sediments (Hayes and Boothroyd, 1969). In a man's lifetime, storms that are geologically significant appear to be rare and isolated events, but on a geological timescale, major storms occur at nearly a steady rate. The problem is still recognizing deposits, assemblages, and features that are the products of storms. Erosion of the beach, cutting of new inlets and blocking of old ones, and formation of washover fans and tidal deltas are examples of the works of storms that can be accomplished in very short periods of time. Unfortunately, similar deposits can also accumulate over a period of time, and the criteria for recognition of storm sedimentation become ambiguous. Probably the net effect of storms is one of major redistribution of sediments; thus, shallow nearshore and shoreline sediments may be carried to environments that are beyond the reach of normal processes which might be expected to return the sediments to their pre-storm position.

Storms commonly result in major alterations in beach profiles and generate cycles of erosion and deposition. Major erosion occurs during the storm, and a flat or concave-upward beach profile is formed. The beach surface is commonly smooth, but a scarp may be eroded along the front of dunes. Soon after the storm has passed, accretion begins with the development of ridge-and-runnel systems, beach cusps, and small berms. After several weeks, the ridges have moved landward up the beach and merged with the backbeach to form a broad berm. In other areas, the ridges may become stationary below the berm and remain on the foreshore surface until removed by a subsequent storm.

The extent of the modification caused by a storm depends on several factors, such as size and intensity of the storm, exposure of the beach relative to the path of the storm, tidal phase, and amount of accretion and beach modification since the last storm. In many areas, there is no summer beach distinct from the winter beach as occurs along many West Coast beaches, and the beach profile is determined by the occurrence and intensity of major storms. However, the frequency of storms is commonly greater in winter than in summer.

Damage associated with hurricanes is ordinarily great and may result in major modification of shore features. Surveys before and after a hurricane passed over the British Honduras reefs indicated catastrophic destruction of reef corals up to 5 to 10 miles from the storm track and defoliation of mangrove within 40 miles (Stoddard, 1962). Large quantities of coral were broken and moved into deep water. Other corals were rolled across the reef flats but remained alive. Low, narrow barrier islands, such as occur along some parts of the Gulf of Mexico coast, may be covered with water during hurricanes. The accompanying large waves may completely erode dunes as well as beaches and wash large volumes of sediments into lagoons landward of the barriers.

SUMMARY

Sediments are moved toward the shoreline by both continental and marine processes, and the environments in the vicinity of the shoreline are therefore an important depositional site. Near the mouths of major rivers, the characteristic deposits are those associated with deltas. At sites somewhat removed from the deltas, but close enough to receive periodic influxes of relatively unsorted sediment from the river, chenier and chenier plain development are favored. At locations some distance from the river, barrier islands develop. The weight of sediment along the shoreline may be sufficient to initiate subsidence, and either transgression or regression occurs, depending on sediment supply. Coasts which have deep water nearshore may lose major quantities of shoreline sediments by transport down submarine canyons to deep-sea fans or by offshore transport during storms.

Along coasts marked by inlets, it is apparent that the shifting of the inlets, under the influence of a dominant longshore current, markedly affects coastal sedimentation. Subsequent transgressions may remove an upper part of the coastal deposits, leaving only the deposits which accumulated in the deep inlets as evidence of the location of a former shoreline.

Changes in the relative elevation of the sea, whether caused by glaciation, water or sediment loading, or tectonism, bring shoreline processes to work on different areas of the land. Storm erosion and deposition cycles, animal communities, surf-base, and the other processes are continually changing their areas of major application.

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COUNCIL ON EDUCATION IN THE GEOLOGICAL SCIENCES
AMERICAN GEOLOGICAL INSTITUTE
2201 M STREET, N. W.
WASHINGTON, D. C. 20037