Beach System

Beaches, along with the accompanying dunes and shoreface environments were established after stabilization of sea level less than 7,000 years ago. Our discussion starts at the strand line since the beach is probably the coastal feature most familiar to readers. The coastal dunes behind beaches and the shoreface regime seaward of the beach are tied together as a beach system with each of these features having unique differences. However, the exchange of sand between them is part of a single system.

Definitions

Beaches are accumulations of unconsolidated sand or gravel that extend from mean low tide to the uppermost extent of wave impact. The best development of beaches is on low lying alluvial coasts, but they are not restricted to these areas. In some locations, they are thin slivers of sand fronting coastal cliffs. Elsewhere, they are broad features backed by wide dune fields and coastal marshes. If North America can be considered typical, more than a third of the world's coastlines are beach environments. Dolan, *et al*.,1972

The beach has three major parts: beach face, berm and backbeach. The beach face is the zone of most active change. Its inclination may vary from a few degrees to as much as 30 degrees. This slope is dependent on both grain size and wave energy which are themselves interdependent. The major factors governing the slope of the beach face and the movement of grains on the slope are: wave height, wave period/length, and grain size of the particles. Grain size is fundamental in controlling percolation of water into the sand and thereby the amount of water in the surface backwash and the amount returning through the beach sediments. This in turn shapes the beach foreshore gradient because the amount of surface return flow is a factor in the movement of sand grains on the beach. Coarse sand beaches with a high degree of percolation have steeper gradients than fine sand beaches because they have less surface backwash and therefore less seaward movement of the grains.

Under conditions that allow beach accretion, the berm forms at the top of the beach face. Except on very flat beaches, the berm has a well-defined crest at the seaward edge. As each wave moves up the beach face, energy is spent in a swash of water carrying sand upward. Since part of the water returns through the beach sand, the backwash is reduced and sand is added to the berm at the crest.

The backbeach behind the berm varies in width and character. The sands of the backbeach are generally fine-grained and well-sorted compared to the beach face. The backbeach and dunes merge into one another and the line of demarcation may shift.

Beaches may be described and differentiated by the character of the materials that comprise them or by the features found in their profiles. The most apparent characters are:

- texture, whether gravel, coarse sand, or fine sand grains form the beach;
- the composition of the particles; and

- slope of the beach.

The texture of beach sediments provides a means of describing different beaches. The main distinction is between gravel or sand beaches, but we may also distinguish fine, medium, or coarse-grained sand beaches. Gravel beaches may result from high wave energies , or may be lag gravel left behind as a coastline containing gravels is eroded . These are formed because wave energy removes sand and fines as erosion proceeds, leaving gravel debris behind.

Beaches may also be categorized by composition of the sediments. The dominant mineral groups are biogenic shell debris (carbonates), quartz and feldspar minerals derived from granitic igneous rocks, dark minerals from basic igneous rocks, and igneous rock fragments from basaltic igneous rocks. The most common beach material is quartz, but in tropical regions, biogenic carbonate grains become important. The spectacular black sand beaches result from nearby volcanic sources supplying dark igneous rock material. Many beaches contain an association of several mineral types . Accessory minerals in beaches include magnetite, micas and augite-hornblende minerals. The beach slope and grain characteristics allow beaches to be described in terms of dissipative and reflective beaches. [Wright and Short, 1983] The beach profiles are different, and the type of wave-breaking and nearshore circulation patterns are different from reflective to dissipative beaches. Dissipative beaches develop under high wave conditions when there is an abundant supply of medium to fine sand. Spilling breakers form and continue as bores across the surf zone, which is wide and has a fairly uniform and gentle slope (see chapter 2 for a discussion of breaking wave types). Dissipative beaches have a wider upper and lower beach face with a slope less than five degrees, and usually lack berm development. [Short, 1984;Smith, 1990]

Reflective beaches form during low to moderate wave conditions when the waves break by plunging or surging followed by strong wave swash up the beach face. The steeper reflective beach face (>10 degrees) transitions to less slope offshore. In higher-energy reflective beaches, there is a berm crest, upper and lower beach face, step and deeper nearshore. Low-energy reflective beaches have only a beach face, step and nearshore zone. In the transition from higher to lower wave energy, the berm remains but it becomes wider with less slope.

Beaches may have seasonal shifts from reflective to dissipative in response to storm and swell conditions. However, a beach of coarse sediments may remain reflective and a fine-sand beach may remain dissipative regardless of wave conditions. [Bryant, 1982]

Coastal sand dunes occur where there is a supply of sand, a wind to move it, and a place for the sand to accumulate. Dune accumulations occur above the spring high-tide line and the backbeach forms the seaward boundary of the dunes and supplies the sand. [Illenberger and Rust, 1988]

Goldsmith [1985] classified dunes as vegetated dunes or transverse dunes (which lack vegetation and generally migrate). Vegetated dunes form ridges parallel to the beach, which are anchored by the vegetation. These are usually a series of dune ridges developed during the accretional history of the coastline. Transverse dune ridges (non-vegetated dunes) have very little anchoring vegetation, and generally move landward in response to the prevailing winds. [Kocurek et al., 1992] Under storm conditions, these dunes may show dramatic encroachment over the landward side. Non-vegetated dunes are especially common in arid climates where there is an adequate supply of sand and a lack of vegetation.

On sandy open coasts, the shoreface is a concave surface between the surf zone and the continental shelf floor, which is morphologically and dynamically distinct from the bordering surf zone and the continental shelf (see figure 5.2). The shoreface varies in width, depth, shape and longshore extent, and it may not be well developed in many locations. This environment is difficult to define and less has been written about its general characteristics than for the other environments of deposition but the potential transfer of sediments across this zone is important. On the mid-Atlantic and New York coasts, the upper shoreface joins the surf zone at about 4 m water depth and the lower shoreface to inner continental shelf transition is at about 25 m. [Liu and Zarillo, 1990]

Physical Parameters

Transformation of wave energy across the shelf, nearshore, and surf zone and the action of onshore winds in transporting wave deposited sand landward are part of a single system of sand input, storage, and loss. The processes discussed in Chapters 1 and 3 act in all of the coastal environments. The effect and control exerted by each process differs with the environment, and has aspects that are unique to each. The dune, beach, and shoreface sand transport is by different forces, but all combine to exchange sand over the combined system.

Breaking waves and consequent onshore-offshore transport, longshore currents and rip currents dominate beach sand transport. Wind bedload transport moves dune sands, and the shoreface transport is from wave asymmetry (see figure 2.24) and ocean currents. These processes act in an environment of tidal and wave interaction on beach systems that are at some stage of physiography between dissipative and reflective. Short and Hesp [1982] described the importance of the shelf slope in controlling the wave energy that is applied to the coastline (Table 5.3). In general, wide and shallow nearshore zones expend more wave energy.

Shelf slope and wave attenuation

shelf slope	wave attenuation (% remaining energy)
1:150	75
1:300	40 - 70
1:800	less than 40

Wave transformation and current development over the shoreface is distinctly different from that in the surf zone and on the continental shelf. Currents affecting the beach are driven by the energy from breaking waves, but seaward of the surf zone, the effects of wind stress, tides, and internal pressure gradients common to the continental shelf are still effective. The shoreface corresponds to an important transition region for ocean waves. A combination of wave and current processes are enhanced and act on bedload transport on the shoreface, just as in the surf and beach zone, but transport parallel to the shore is much less in the shoreface than in the surf zone. [Niedoroda, *et al*., 1984]

Entrainment and transportation of sediments by wind follows similar patterns to those initiating sediment movement in water. Particles move when the shear stress from the wind exceeds a critical value that is related to grain size, density and slope. Because of the large differences of density between sand grains and air, transportation by suspension is relatively unimportant in coastal dunes. Sand movement in a dune is generally by creep (bed-load) and saltation (see discussion of sediment transport, chapter 3). Sand is removed from the windward face and transported to the lee face, where it is deposited and accumulates at the angle of repose.

Dissipative beaches have the largest foredunes because their width allows drying of the upper beach face resulting in maximum potential sand transport by onshore winds during low tide. On a reflective beach, sand transport is minimal due to the usual presence of wet sand and swash. Only on the backbeach, which is generally removed from wave influence, is the sand dry enough for grain movement by wind action.

Sedimentary Structures and Features

The processes that occur along the beach are recorded in the sedimentary structures left within the accreting beach face. Where old berms have been eroded and new foreshore sediments deposited, cross-bedding may develop. The layering observed is often accentuated by the presence of dark layers that form as the result of larger waves concentrating heavy minerals. Migrating shores and cross bedding formation illustrate a beach that is in the process of building out under the influence of fair-weather waves and developing cross-bedding.

Cross-bedding is also a fundamental feature of the internal structure of dunes . Advances and retreats of dune faces, vegetation, and wind shifts all contribute to variation in the bedding planes, leading to cross-bedding and erosional unconformities. Low-angle cross-beds form as sand accumulates around the dune vegetation, which acts as a baffle, trapping the wind-blown sand.

The surge of water up the beach face above the still water line is the swash zone. The upper limit is often shown by a swash mark . As the tide is going out, several of these lines may be seen. Swash marks are left where the top of a wave comes to a halt up the beach face and water sinks into the sand leaving behind lines of beach debris, mica or lighter carbonate grains (i.e. *Halimeda* grains) as part of the swash water flows by percolation through the sand.

Several types of beach ripples form on the foreshore. Backwash ripples develop on fine sand beaches because of the backwash of waves setting up turbulent motion. Within the runnel between the ridge and the beach face, large ripples form as water drains away perpendicular to the beach at low tide. Rip channels and strong tidal current channels have large current ripples. Current ripples have an asymmetric shape that shows the direction of current flow. Wave ripples formed by oscillatory motion are symmetric and peaked. A combination of longshore current ripples and approaching wave oscillation ripples may result in a pattern of cross ripples.

Eolian ripples , which have a similar shape to current beach ripples, form on all parts of the dunes and upper beach. Many of these ripples accumulate in an echelon or linear chains and display a striking resemblance to barchan dunes in form and movement.

The beach foreshore may have a step just seaward of the swash zone. This is an abrupt drop in the foreshore profile that occurs at the point where the wave swash flowing back down the beach meets the next incoming wave. The step has changes in sand texture, being marked at the top by a concentration of coarser sediment than the rest of the beach face. Steps are usually developed where tidal ranges are low and the foreshore slope is steep; they are therefore usually associated with reflective beaches.

Cusp-shaped points are common along beaches. These sand points grade in size from small beach cusps to large cuspate forelands. Large seaward projecting accumulations of loose marine sand or gravel form cuspate forelands . Ideal sites for the formation of cuspate forelands include those locations where a major change in coastline direction occurs. Many cuspate forelands have been built by the progradation of a series of beach and dune ridges as sediments are deposited in the slack water zone between two coastal eddies. Eddies commonly develop inside a major current that flows along the coast, such as the Gulf Stream. Some small cuspate forelands are formed by progradation of beaches on the inside of small islands or other obstructions.

Small beach cusps with points facing the sea and rounded embayments between the points occur on coarse sand beaches but only sporadically on fine sand beaches. Spacing of the cusps is related to the height of the waves when the cusps were formed. [Komar, 1976] The swash cusps are formed by the swash and backwash acting on the beachface and berm. Swash runs up the beachface to the apex of a cusp where it swings into a longshore direction and flows as backwash forming the cusp valley. [Inman and Guza, 1982] Cusps scallop the beach into regular forms, but do not change the overall alignment of the beach. Development of cusps occurs during an approach of waves parallel to the coast, and destruction may follow a change to diagonally approaching waves. Giant cusps are formed by a nearshore circulation cell and shape the beach on a scale that is of the order of the surf zone width.

Carbonate beaches are subject to rapid cementation in the foreshore environment compared to siliciclastic beaches. This leads to the rapid development of seaward dipping slabs of beachrock. Beachrock can be broadly defined as lithified beach sand (calcarenite) which occurs in bands along the intertidal zone. Beachrock cements are precipitated from either marine or freshwater in the intertidal zone of the world's tropical and subtropical beaches.

Under tropical conditions, dune sand composed of calcium carbonate rather than quartz is common. Most carbonate dunes are deposited adjacent to high energy beaches in warm climates where abundant carbonate grains are present. These dunes develop in a manner similar to siliciclastic dune formation and few differences are found between quartz and carbonate dunes in either the developmental processes or in the resulting dune forms. Dune sands will contain skeletal and non-skeletal grains supplied by the beach sands and fossils of terrigenous organisms as available.

During the rainy season, calcium carbonate from the shell fragments goes into solution. During the long dry season, the calcium carbonate precipitates, forming cement, which will produce a distinct type of lithified coastal rock, referred to as an eolianite or fossil dune accumulation. Generally eolianites are well-sorted, cross-bedded, and preserve all of the features of an unconsolidated dune.

The Coastal Sediment Budget

Since beaches receive material from various sources, they would grow continuously except for the equilibrium of supply and loss from onshore/offshore and longshore transport. This movement, together with sources of sand input, loss and storage, make up the sand budget for a beach system. The sand budget includes transfer of sand between dunes, beach and shoreface.

Sand sources for the beach include river discharge which may supply material directly to the beach or supply it to the nearshore for later beach nourishment. The source of much beach sand is the shallow sea floor, where sand was carried by runoff from land areas and the sediments passed beyond the beach system. This source may include sands that were deposited on the continental shelf during Pleistocene low sea level (relict sands). This is an important source in areas where streams are not introducing appreciable amounts of material, and where no alluvial or soft rock cliffs supply sand. The marine shelf is also a source of biogenic sediment production that may be moved into beach systems. Sea cliffs and low alluvial plains are an important source of sediment if they are unconsolidated, in which case those exposed to the open sea may recede several meters per year.

Beaches may lose sand into dune systems when the sediments are carried inland. Offshore transport of sand may become lost where the slope becomes too steep for return of sand. Offshore transport from storm conditions or rip currents that move sand out of the system, and transport into submarine canyons will also result in sand loss.

Water brought to the shore by breakers and translatory waves causes longshore currents close to the beach which transports sand out of one beach and into another. At variable intervals, longshore transported water turns seaward to form outgoing rip currents. When rip currents are well established, the sea floor in the surf zone is truncated by channels of the rips and their feeder currents. Rip currents selectively remove sand beach. Large rips transport significant quantities of sediment to the inner continental shelf and in areas of high energy, rip currents carry sand from the beach beyond the breakers and onto the inner continental shelf where a wedge of fine sand is created. During calm periods, some of this sand may be returned to the beach.

Some of these processes provide temporary storage for sand and may allow later return to the beach. Dunes, coastal sands and offshore deposits from river discharge may be transferred into the beach system after a break in time. The dune contribution to sand storage is small. The volume of dune sand compared to the visible beach is impressive, but when considered as part of a system extending beyond the shoreface, it is only a small part. Transfer from upcurrent beaches provides material to many beach systems and transfer down current by longshore transport is loss. Large amounts of sand can be moved in this manner. If a beach terminates with a rocky point, the sand in longshore transport may be deflected offshore and lost, instead of moving into the next beach. Supply and loss from beach systems may be part of the same process, and imbalance in exchange will result in a net gain or loss of shoreline.

Bars returning to the beach prism include shoreface sands. [Niedoroda, *et al*., 1984] After a storm, swells push the bar system landward and eventually the wave formed bar is welded onto the beach. With additional sediments added to the beach, a berm builds and the beach becomes convex upward. Beach erosion and reconstruction are often cyclic, but do not necessarily follow seasons.

A coupled area of erosion and deposition alongshore is a coastal cell . Cells are complete and self-contained sediment budget systems within a limited geographical area, which may not have physical boundaries. Within a cell, we may have continuity of sediment influx from the sources (rivers) through the pathway (surf zone) and into sinks offshore. An analysis of individual cells can be undertaken with computer programs if wave data and near-shore bathymetry are known. Modification of the cell geometry and budget by dredging, filling or morphology change can be modeled. The volume of sediment transported alongshore is much greater than the volume transported offshore/onshore along most coastal cells. Many beaches are highly compartmentalized , with very little communication between individual beaches.

Beach Erosion and Storms

Beach erosion is a matter of sediment transport and the beach budget when sand moves from an eroding area to an area of accumulation. A change in the sediment budget can result from natural causes such as sea level change, with an adjustment of the beach position, or an interruption in the supply of sediment by storage in inlets, diversion offshore, loss of source, etc. Coastal erosion and accretion are natural processes and erosion becomes a problem only when property is threatened with destruction.

Coastlines may extend seaward or retreat landward as a response to glacial processes that raise or lower sea level; and they may change due to seasonal and short term sea level fluctuations and weather patterns. These changes result in changes of rate of shoreline movement of centimeters to several meters per year, but 20 to 30 meter losses that have been seen in the span of a single year are often caused by man's intervention.

The rate of erosion or progradation of the coastline may be estimated by beach profiling to show changes or by measuring the change of shoreline position in time from aerial photographs . The volume of sediment in transport on an average annual basis can be estimated by use of shoreline change maps and beach profile lines. [Morelock, 1987] An important factor in the determinations using profile lines is the limiting offshore depth to which computations are carried. This " closure depth " may be estimated from repetitive bathymetric profiles as the depth beyond which little or no change in depth occurs over time. This is about six meters for the U.S. Atlantic coast.

Examination of the coast by aerial reconnaissance, beach surveys, and comparative analysis of aerial photographs shows that there is severe erosion on many coasts. Of the total world's coastline, more than 20 percent is sandy depositional terrain with beaches. Less than 10 percent of these have had recent progradation while 70 percent have been eroding, and the balance (20-30 percent) appear stable. [Pilkey, 1991] These are not very encouraging numbers for development of beachfront property.

The character of the beach face can change dramatically over time depending on wave conditions. Under calm wave conditions, sand moves onshore and the beach builds into a broad feature with a well-developed berm. Fair weather waves tend to be swells of low amplitude and long period. The asymmetry of the associated bottom wave surge is marked, with the landward stroke beneath the wave crest being significantly more intense than the seaward stroke beneath the trough. Differential velocity is sufficient to move sand upslope and onshore except in zones of rip currents. This onshore migration is particularly large during a time of long period waves.

As wave steepness increases under storm conditions, wave surge asymmetry is no longer efficient in driving coarser sand landward as bed load. More sand is thrown into suspension and the critical grain-size threshold between suspensive and tractive sand fractions is shifted to favor suspension. The berm is cut back or disappears entirely during storms and the overall beach foreshore becomes more gently sloping, although a beach scarp may form on the foreshore as the result of excessive cutting at one level. The offshore zone ordinarily develops rather deep channels due to strong longshore currents, and the sand that has been eroded from the beach is often stored in offshore bars. Some sand is driven across the back beach and over the dunes in the form of a washover fan . During a severe storm, the seaward shift in breaker position and the intensification of seaward sand transport may destroy the bar and beach prism, with heavy transport in rip channels and rip current plumes. The sand washed off the foreshore by backwash does not settle and is often carried into rip currents and transported seaward out of the system while creating a series of eroded channels (see figure 5.17). The result is withdrawal of littoral sand from the fair weather storage. Immediately after storms, the upper beach profile is very steep and may have an eroded scarp.

After a storm has passed, waves return to normal and sand gradually moves back onto the beach. This is often accomplished by the landward migration of sandbars that were created during the storm. As these bars approach the beach, they form broad ridges that are moved landward in steps with each rise and fall of the tide. In 1944, the ridge-and-runnel system off the Normandy coast played a major role in the invasion. The beach landing, planned for the previous week, had to be postponed due to storms in the English Channel. Earlier scouting reports had described a broad beach with easy access to the coast at all stages of the tide. After the storm, however, as the beach recovered, wide and high ridges marched toward the beach. When the invasion force landed near mid tide, they found not the easily accessible shoreline that had been reported, but rather exposed ridges separated from the main beach by water. We know today that the water depth in the runnels can be over two meters deep at Normandy, as the soldiers unfortunately learned the hard way. Since this hard lesson, the U.S. Navy has expended considerable effort into understanding the nature of these and other coastal processes that might have military significance.

On the west coast of the U.S., this cycle follows seasonal patterns with winter swell eroding the beaches and calmer summer conditions encouraging accretion. Shepard [1973] referred to these two end members as winter beaches and summer beaches, respectively. On the east coast, Shepard's "winter profile" develops as strong storms generated in the tropics make their way up the eastern seaboard. While these storms often occur in the winter, the steep post-storm profile is by no means confined to the winter months.

Interaction between storm erosion and wind transport is cyclic. As a dune is reached by waves, its sand spreads over the storm wave swash zone. Sand released from the dune replaces the berm and sand on the visible beach foreshore becomes finer, since the dune has finer sand. This tends to flatten the swash zone surface so the final wave runup expands landward as the wave attack on the dune accelerates. The wave bore striking the dune then generates a near vertical scarp in the dune that becomes progressively taller. This scarp changes the wave bore uprush behavior. Instead of running up an even slope, the bore now strikes a near vertical face, and the kinetic energy of the bore is converted into potential energy as the bore stalls. The reflection back down the beach face reduces incoming energy, and the dune scarp is capable of handling more incoming wave energy than a low sloping continuous swash zone. [Smith, 1988]

Major shoreface sediment transport is even more episodic and storm related than surf zone sand transport. Shoreface bedload transport can extend between the surf zone and the inner shelf during even moderate storms. Sediment removed from the surf zone by storms is deposited across the shoreface with most being deposited on the upper shoreface. The stripping of sediments from the beach leaves a concave upward profile to the beach face. Transport and deposition of the sediment is across the entire shoreface and onto the continental shelf. Most sand transferred by storms from the beach to the upper shoreface will eventually be returned to storage in the beach prism but during strong storm conditions, the upper shoreface is not a closed system. A significant portion of the sediment is transported across the shoreface and lost to deposition on the inner continental shelf.

Links

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