BEACHES, PHYSICAL PROCESSES AFFECTING

A. D. Short, University of Sydney, Sydney, Australia

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Introduction

Beach systems occur on shorelines throughout the world and are a product of three basic factors – wave, sediment, and substrate. They are, however, also influenced by tides and impacted by a range of geological, biotic, chemical, and temperature factors. Beach systems therefore occupy a considerable range of environments, from the picturesque tropical beaches, to those exposed to the full forces of North Atlantic storms, to the usually frozen shores of the Arctic Ocean. In addition formative waves can range from low to extreme, and sediment from fine sand to boulders. This article looks at how the two main processes – waves and tides – interact with sediment to form three types of beach systems: wave-dominated, tide-modified, and tide-dominated, the three representing all the world's beach types. It then considers some of the major factors that modify beach systems on a global and regional scale, including geology, temperature, biota, and chemical processes.

Beaches

Beaches are a wave-deposited accumulation of sediment lying between wave base and the limit of wave uprush or swash. The wave base is the seaward limit or depth from which average waves can entrain and transport sediment shoreward. The essential requirements for a beach to form are therefore an underlying substrate, sediment, and waves. In two-dimensions as waves shoal across the nearshore zone, between wave base and the breaker zone or shoreline, they generate a concave upward profile. As the waves transform at breaking to swash, the swash builds a steep beach face or swash zone, which caps the beach system.

In reality beaches are usually more complex. Waves can range in size from a few centimeters to several meters, and period from 1 to 20 s, and additional processes, particularly tides influence both the waves and the resulting beach morphology. Beaches can also be composed of sediments ranging from fine sand to boulders. In addition, the underlying substrate, known as the geological inheritance provides both the two-dimensional foundations, as well as potential two- and three-dimensional irregularities such as reefs and headlands, all of which influence wave transformation, sediment transport, and two- and three-dimensional beach morphology. Finally when waves break across a surf zone, they generate three-dimensional flows that produce a more complex three-dimensional surf zone and beach morphology, that lies between the nearshore and swash zones. Beaches, therefore, all contain a nearshore zone dominated by wave shoaling processes; they may contain a surf zone dominated by wave breaking and surf zone currents, and finally a swash zone dominated by wave uprush and backwash (**Figure 1**).

Beaches also range from relatively simple low-energy, two-dimensional, tideless systems with waves surging against a uniform shoreline, to more complex higher energy systems, incorporating surf zones with three-dimensional circulation, such as rip currents, associated with highly rhythmic bars and shorelines. In addition geological inheritance can introduce a wide spectrum of bedrock and sedimentology inputs that cause additional wave transformation through variable wave refraction and attenuation, as well as influence sediment type and mobility.

This article will cover the full range of physical beach systems from the low to high wave energy wave-dominated beaches. It will then address the influence of increasing tide range in the tide-modified and tide-dominated beaches. Finally it will briefly review the role of geology (e.g., headlands and reefs) and other physical, chemical, and biotic factors in modifying beach systems.

Wave-dominated Beaches

Wave-dominated beaches occur in environments where waves are high relative to the tide range. This can be defined quantitatively by the relative tide range (RTR)

$$RTR = TR/Hb \qquad [1]$$

where TR is the spring tide range and Hb the average breaker wave height. When $RTR < 3$ beaches are wave dominated, when $3 < RTR < 15$ they are tide-modified and when the $RTR > 15$ they become tide-dominated.

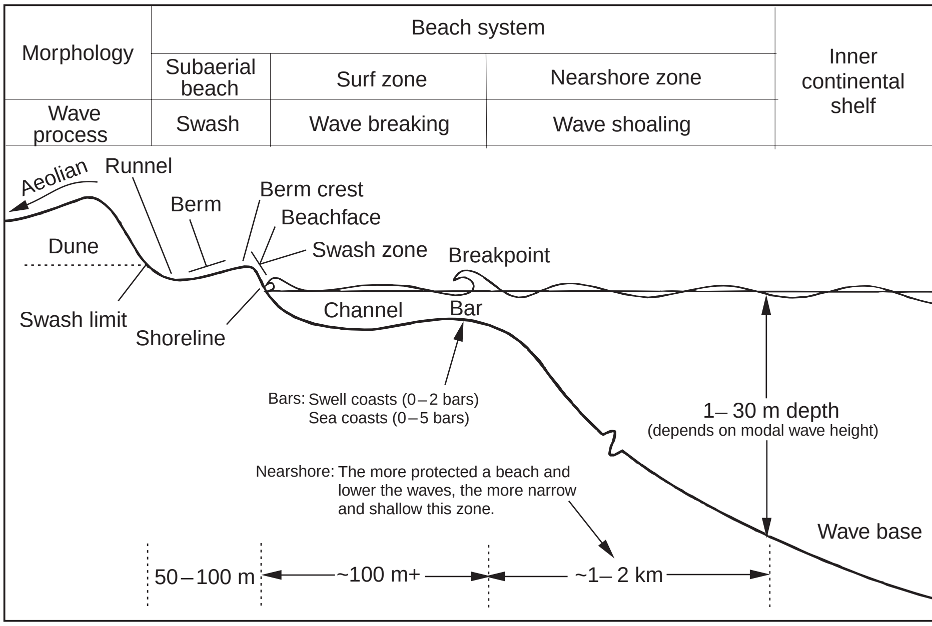

Figure 1 Definition sketch of a high-energy wave-dominated beach system. The beach contains a subaerial beach dominated by swash, a surf zone dominated by breaking waves and the nearshore zone across which waves shoal. (Reproduced from Short, 1999.)

Within any beach environment, wave height and period and sediment size can all vary substantially. In order to accommodate the potentially wide range of wave height–period–sediment combinations **Figure 2** presents a sensitivity plot which defines the three wave-dominated beach types, reflective, intermediate and dissipative, using the dimensionless fall velocity

$$\Omega = \mathrm{Hb}/T\mathrm{Ws} \qquad [2]$$

where T is wave period (s) and W_s is sediment fall velocity (ms^{-1}).

Reflective Beaches

Reflective beaches occur when $\Omega < 1$, which requires a combination of lower waves, longer periods and particularly coarser sands. They occur on sandy open swell coasts when waves average less than 0.5 m, and on all coasts when beach sediments are coarse sand or coarser, including all gravel through boulder beaches. On gravel–boulder reflective beaches waves may exceed a few meters. They are, however, all characterized by a nearshore zone of wave shoaling that extends to the shoreline. Waves then break by plunging and/or surging across the base of the beach face. The ensuing strong swash rushes up the beach, combining with the coarse sediments to build a steep beach face, commonly capped by well-developed beach cusps and/or a berm (**Figures 3** lower and **4**). When the sediment consists of a range of grain sizes, the coarser grains accumulate as a coarser steep step below the zone of wave breaking, at the base of the beach face.

Reflective beaches therefore consist of a concave upward nearshore zone composed of wave ripples and relatively fine sand across which waves shoal. As the waves break at the base of the beach there may be a coarser step up to a few decimeters high, then a relatively steep (4–10°) beach face, possibly capped with cusps. The cusps are a product of cellular circulation on the high tide beach resulting from subharmonic edge waves produced from the interaction of the incoming and reflected backwash. The high degree of incident wave reflection off the beach face is responsible for naming of this beach type, i.e., reflective. Apart from the cosmetic beach cusps and swash circulation, if present, these are essentially two-dimensional beaches with no alongshore variation in either processes or morphology. On sand beaches they also represent the lower energy end of the beach spectrum and as such are relatively stable systems, only experiencing beach change during periods of higher waves which tend to erode the berm and deposit it as an attached low tide bar or terrace (**Figure 3** lower). During following lower waves the terrace quickly migrates back up onto the beach as a new berm or cusps.

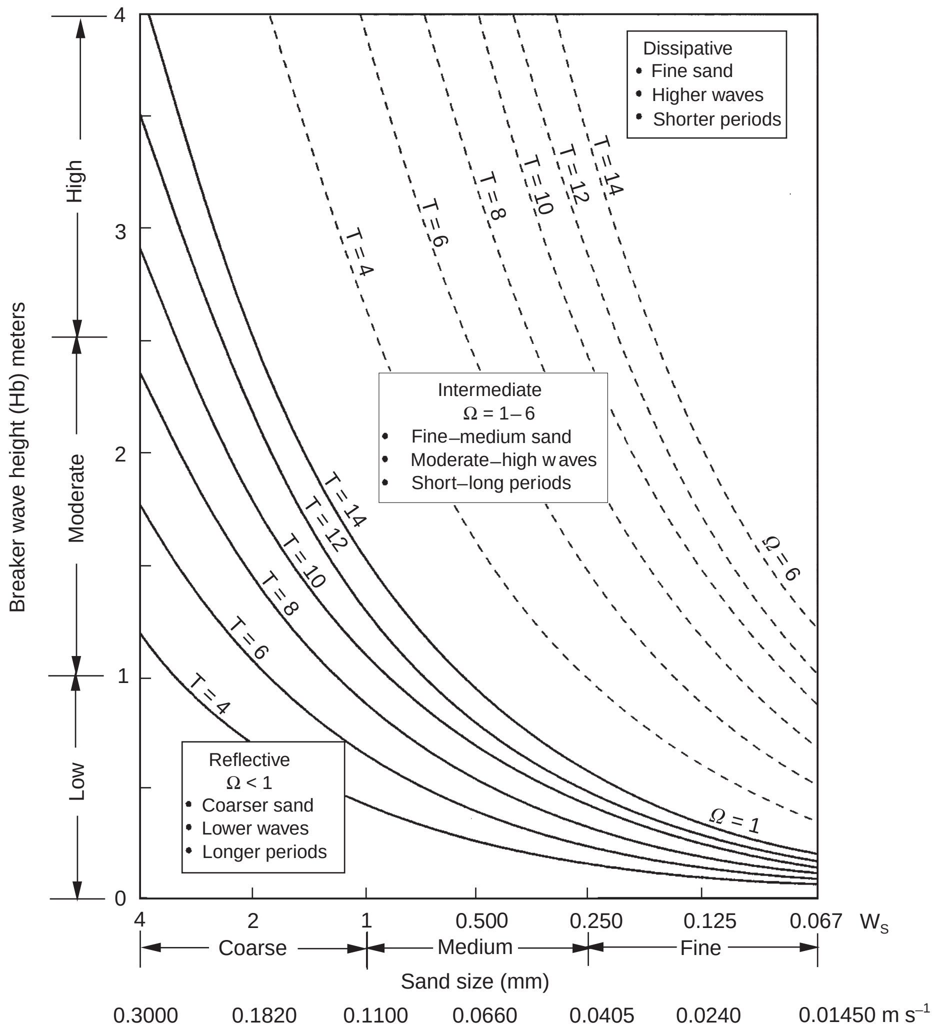

Figure 2 Sensitivity plot of the contribution of wave height, sediment size and wave period to Ω and beach type. To use the chart determine the breaker height, period (T) and grain size/fall velocity (phi or m s^{-1}). Read off the wave height and grain size, then use the period to determine where the boundary of reflective/intermediate, or intermediate/dissipative beaches lie. $\Omega = 1$ along solid T lines, and $\Omega = 6$ along dashed T lines. Below the solid lines $\Omega < 1$ the beach is reflective, above the dashed lines $\Omega > 6$ the beach is dissipative, between the solid and dashed lines Ω is between 1 and 6 and the beach is intermediate. (Reproduced from Short, 1999.)

Intermediate Beaches

Intermediate beaches are called such as they represent a suite of beach types between the lower energy reflective and higher energy dissipative. They are the beaches that form under moderate (Hb > 0.5 m) to high waves, on swell and seacoasts, in fine to medium sand (**Figure 2**). The two most distinguishing characteristics of intermediate beaches is first a surf zone, and second cellular rip circulation, usually associated with rhythmic beach topography. Since intermediate beaches can occur across a wide range of wave conditions, they consist of four beach states ranging from the lower energy low tide terrace to the high energy longshore bar and trough (**Figure 3**).

Intermediate beaches are controlled by processes related to wave dissipation across the surf zone which transfers energy from incident waves with periods of 2–20 s, to longer infragravity waves with periods > 30 s. As a consequence, incoming long waves associated with wave groupiness, increase in energy and amplitude across the surf zone and are manifest at the shoreline as wave set up (crest) and set down (trough). They then reflect off the beach leading to an interaction between the incoming and outgoing waves to produce a standing wave across the surf zone. It is believed that standing edge waves trapped in the surf zone are responsible for the cellular circulation that develops into rip current circulation, that in turn is responsible for the high

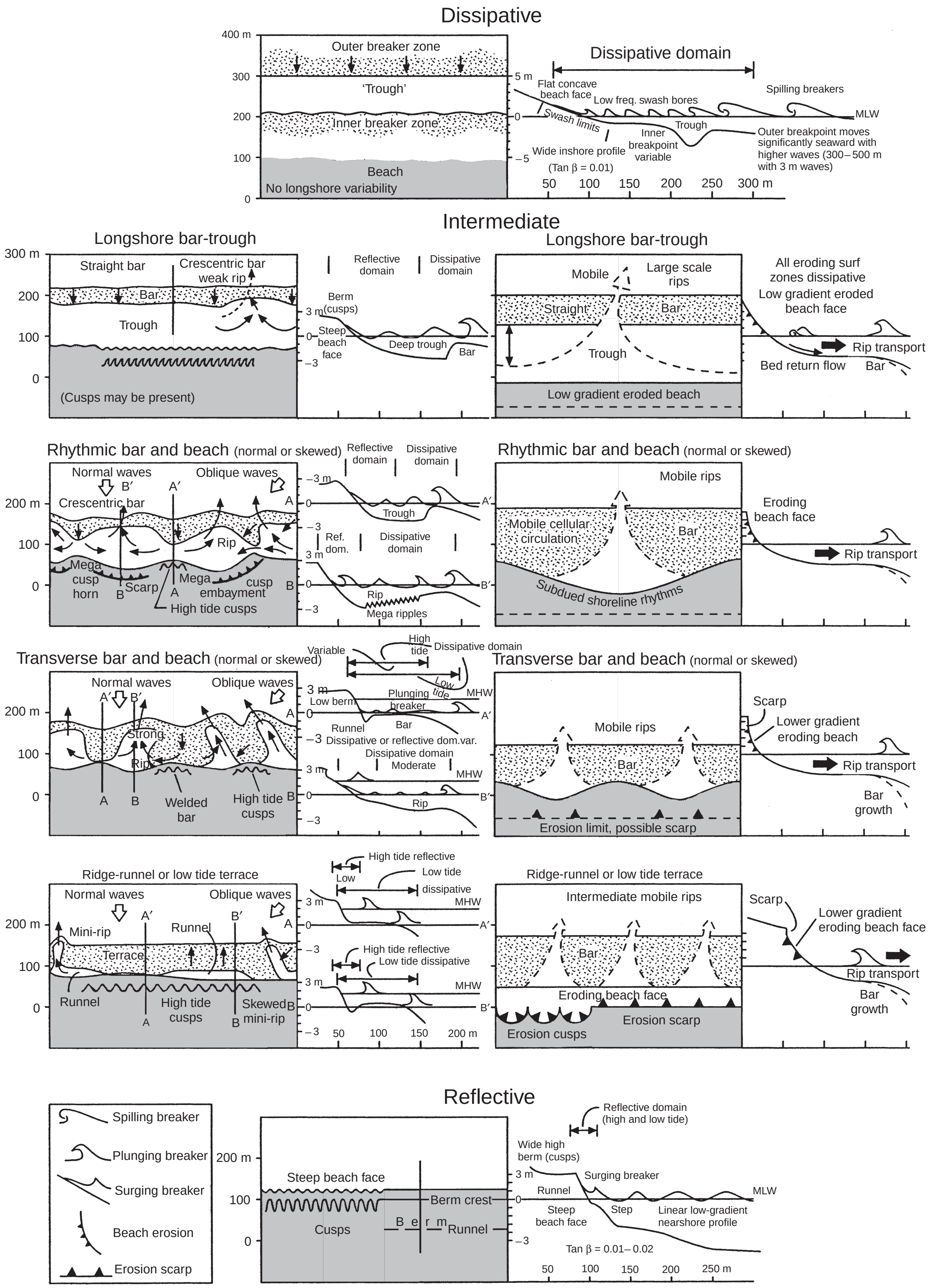

Figure 3 Three-dimensional sequence of wave-dominated beach changes for accretionary (left) and erosional (right) wave conditions. The sequence ranges from dissipative (top), through intermediate, to reflective (lower). (Reproduced from Short, 1999.)

Figure 4 Pearl Beach near Sydney, Australia, is a modally reflective beach composed of medium to coarse sand and receiving usually lower swell waves. Note the very narrow zone of wave breaking, well-developed beach cusps and cusp-controlled segregated swash circulation (A.D. Short).

degree of spatial and temporal variability in intermediate beach morphodynamics.

Low tide terrace Low tide terrace (or ridge and runnel) beaches are characterized by a continuous attached bar or terrace located at low tide (**Figure 5**). Usually smaller waves (0.5–1 m) break across the bar at low tide, whereas at high tide they may remain unbroken and surge up the reflective high tide beach face. At mid to low tide cellular circulation in the surf zone usually produces weak rip current flows, which may be transitory across a planar bar, or may reside in shallow rip channels (mini-rips) (**Figure 3**).

Transverse bar and rip Transverse bar and rip beaches form under moderate waves (1–1.5 m) on swell coasts. They consist of well-developed rip channels, which are separated by shallow bars, which are attached and perpendicular or transverse to the beach. Variable wave breaking and refraction across the shallow bars and deeper rip channels leads to a longshore variation in swash height and approach, which reworks the beach to form prominent megacusp horns, in lee of bars, and embayments, in lee of channels (**Figures 3** and **6**). Water tends to flow shoreward over the bars, then into the rip feeder channels. The flow moves close to the shoreline and converges laterally in the rip embayment. It then moves seaward in the rip channel as a relatively narrow (a few meters), strong flow ($0.5\text{–}1\,\mathrm{m\,s^{-1}}$), called a rip current. The current usually moves through the surf zone and beyond the breakers as a rip head. This beach state has extreme spatial–longshore variation in wave breaking, surf zone and swash circulation, and beach and surf zone topography, leading to a high unstable and variable beach system.

Rhythmic bar and beach The rhythmic bar and beach state forms during periods of moderate to high waves (1.5–2 m) on swell coasts. The high waves lead to greater surf zone discharges that require deeper and wider rip feeder channels and rip channels to accommodate the flows. Rips flow in well-developed rip channels, separated by transverse bars, but the bars are detached from the beach by the wider feeder channels (**Figure 7**). The bar is highly rhythmic moving seaward where rips exit the surf, and shoreward over the bars, whereas the shoreline is also highly rhythmic for the reason stated above. It is not uncommon for the more energetic swash in the rip embayments to scarp the beach face, while the adjoining horns are accreting (**Figure 3**).

Figure 5 A wide, well-developed low tide terrace at Crowdy Head, New South Wales. Note the transition from transverse bar and rips (foreground) to mini-rips, then continuous low tide terrace (A.D. Short).

Figure 6 Well-developed transverse bar and rip beach with high rhythmic shoreline (megacusp horns and embayments), attached bars and well-developed rip channels, Johana Beach, Victoria (A.D. Short).

Figure 7 Rhythmic bar and beach at Egmond, The Netherlands. Note the shoreline rhythms and detached crescentic bar (A.D. Short).

Longshore bar and trough The longshore bar and trough systems are a product of periods of higher waves which excavate a continuous longshore trough between the bar and the beach. Waves break heavily on the outer bar, reform in the trough and then break again at the shoreline, often producing a steep reflective beach face (coarser sand, **Figure 3**) or a low tide terrace (finer sand). On swell coasts waves must exceed 2 m to produce this intermediate beach state. The high level of surf zone discharge excavates the deep trough to accommodate the flow. Surf zone circulation is both cellular rip flows, as well as increasingly shore normal bed return flows (see below).

Dissipative Beaches

Dissipative beaches represent the high-energy end of the beach spectrum. They occur in areas of high waves, prefer short wave periods, and must have fine sand. They are relatively common in exposed sea environments where occasional periods of high, short storm waves produce multibarred dissipative beach systems, as in the North and Baltic seas. They also occur on high-energy midlatitude swell and storm wave coasts as in northwest USA, southern Africa, Australia, and New Zealand. On swell coasts waves must exceed 2–3 m for long periods to generate fully dissipative beaches. They are characterized by a wide long gradient beach face and surf zone, with two and more shore parallel bars forming across the surf zone (**Figures 3** upper and **8**). The low gradient is a product of both the fine sand, and the dominance of lower frequency infragravity swash and surf zone circulation, which act to plane down the beach. Their name comes from the fact that waves dissipate their energy across the many bars and wide surf zone. The dissipation of the incident wave energy leads to a growth in the longer infragravity energy, which becomes manifest as a strong set up and set down at the shoreline. The standing wave generated by the interaction of the incoming and outgoing waves may have two or more nodes across the surf zone. It is believed that the bar crests from under the standing wave nodes and troughs under the antinodes. Surf zone circulation is vertically segregated. Wave bores move water shoreward toward the surface of the water column. This water builds up against the shoreline as wave set up. As it sets down the return flows tends to concentrate toward the bed, which propels a current across the bed of the surf zone (below the wave bores) called bed return flow.

Like the reflective end of the beach spectrum dissipative beaches are remarkably stable systems. They are designed to accommodate high waves, and can accommodate still higher waves by simply widening their surf zone and increasing the amplitude of the standing waves, while periods of lower waves are often too short to permit substantial onshore sediment migration.

Figure 8 Aracaju Beach in north-east Brazil is a well-developed double bar dissipative beach produced by persistent trade wind waves breaking across a fine sand beach. Note the straight beach scarp, a characteristic of dissipative beach erosion. Photograph by AD Short.

Bar Number

All dissipative beaches have at least two bars and in sea environments commonly have three or more, with up to 10 recorded in the Baltic Sea. In addition, whereas the reflective and intermediate beaches described above assume one bar, all may occur in the lee of an outer bar or bars. In energetic waves the number of bars can be empirically predicted by the bar parameter

$$B^* = \chi_s / g \tan \beta T^2 \qquad [3]$$

where χ_s is the distance to where nearshore gradient approaches zero, g is the gravitational constant and $\tan \beta$ the beach gradient. Bar number increases as the gradient and/or period decrease, with no bar occurring when $B^* < 20$, one bar between 20–50, and two or more bars > 50.

In two or more bar environments sequential wave breaking lowers the height across the surf zone. As a consequence, Ω (eqn [2]) decreases shoreward and the bar type adjusts to both the lower wave height and Ω. A common multibar sequence is a dissipative outer (storm) bar, with more rhythmic (intermediate) inner bar/s, and a lower energy beach (reflective/low tide terrace).

Modes of Beach Change and Erosion

Figure 3 illustrates an idealized sequence of wave-dominated beaches from dissipative to reflective. It also suggests that beaches can change from one type or state to another, either though beach accretion (movement downward, on left side) or beach erosion (upward, on right side). Beach change, whether erosion or accretion is simply a manifestation of a beach adapting to changing wave conditions by attempting to become more reflective and move sediment shoreward (lower waves) or more dissipative and move sediment seaward (higher waves). Shoreward sediment movement normally requires onshore bar migration, leading in **Figure 3**, from a longshore bar and trough, to a rhythmic bar and beach, the bars then attaching to the beach in the transverse bar and rip, the rips infilling at the low tide terrace, and finally migrating up onto the reflective beach. The rip channels tend to remain stationary during beach accretion, as they are topographically fixed by the bars. Conversely, higher waves and greater surf zone discharges require a wider and deeper surf zone to accommodate the flows. Sediment is eroded from the beach faces and inner surf zone (see scarps, **Figure 2**) and moved seaward to build a wider bar/s. Large erosional transitory rips and increasingly bed return flow transport the sediment seaward.

In nature, movement through this entire sequence is rare, requiring several weeks of low waves for accretion, and many days of high waves for the full erosion. In reality waves rarely stay so low or so high long enough, and most beaches shift between one of two states as they adjust to ever-changing wave conditions, particularly in swell environments. In sea environments, calm periods between storms lead to a stagnation of often high-energy beach topography, which will await the next storm to be reactivated.

Tide-modified Beaches

Most of the world's beaches are affected by tide. On most open coasts where tides are low (< 2 m) waves dominate and tidal impacts are minimized, as in the wave-dominated systems. However, as tide range increases and/or wave height decreases tidal influences become increasingly important. To accommodate these influences beaches, still by definition wave-formed, can be divided into three tide-modified and three tide-dominated types, as defined by eqn [1].

The major impact of increasing tide range is to shift the location of the shoreline between high and low tide, depending on the shoreline gradient, by tens to hundreds of meters. This shift not only moves the shoreline and accompanying swash zone, but also the surf zone, if present, and the nearshore zone. Whereas wave-dominated beaches have a 'fixed' swash–surf–nearshore zone, on tide-modified beaches they are more mobile. The net result is a smearing of the three dominant wave processes of shoaling (nearshore zone), breaking (surf zone) and swash (swash zone), as a section of intertidal beach can be exposed to all three processes at different states of the tide. Because all three zones are mobile, except for a brief period at high and low tide, there is a reduction in the time any one process can fully imprint its dominance on a particular part of the beach. As a consequence there is a tendency for swash processes to dominate only the spring high tide beach, for surf zone processes to dominate only the beach morphology around low tide, during the turn of the low tide, while the shoaling wave processes become increasingly dominant overall, producing a lower gradient more concave beach cross-section.

If we take the three wave-dominated beach types and increase tide range to an RTR of between 3 and 15 the following three beach types result.

Reflective Plus Low Tide Terrace

When $\Omega < 2$ and $\mathrm{RTR} > 3$ the high tide beach remains reflective, much like its wave-dominated

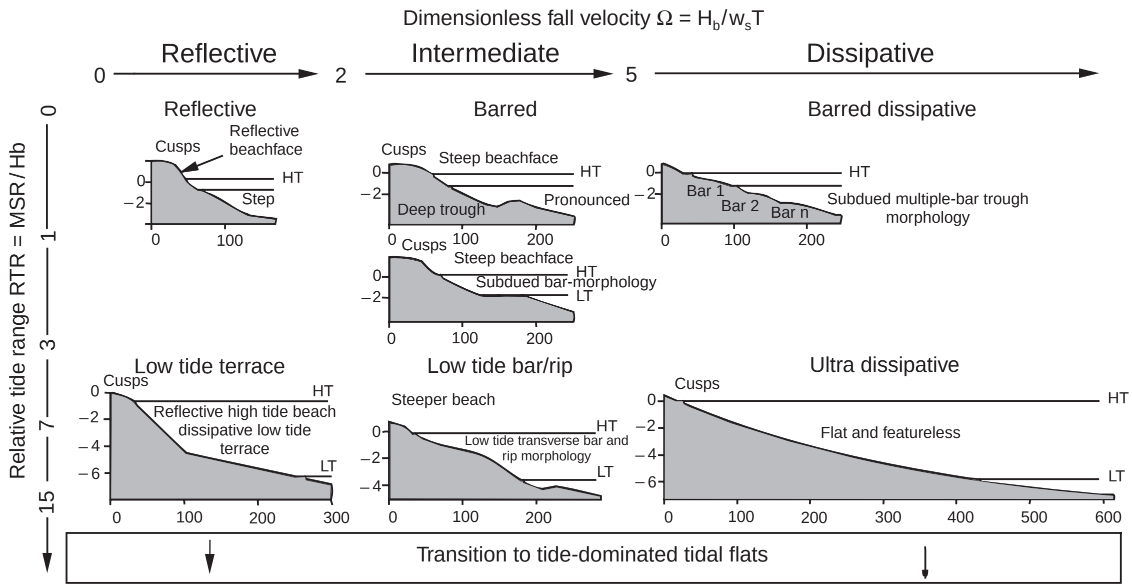

Figure 9 A simplified classification of beaches based on the dimensionless fall velocity and relative tide range. Wave-dominated beaches (top) have an RTR < 3, whereas tide-modified beach types have RTR 3–15 (lower). (Reproduced from Short, 1999.)

counterpart. However, the higher tide range leads to an exposure of the inner nearshore zone, which when swept by surf and swash processes becomes an attached low tide terrace (**Figure 9**). It has a sharp break in slope between the steep beach face and flatter terrace at the point where the water table exits from the beach (**Figure 10**). The low tide drainage from the beach is another feature of tide-modified beaches. At low tide waves dissipate across the flat terrace, whereas at high tide they surge across the steep reflective high tide beach.

Reflective Plus Low Tide Bar and Rips

In areas of moderate waves ($\Omega = 2$–5) and tide range (RTR = 3–7) the tide-modified beaches consist of a high tide reflective beach, a usually wider intertidal zone, which may contain transitory swash ridges, and a low tide bar dominated by surf zone morphology, which may include transverse and rhythmic bars and rips. The surf zone processes, including the rips currents, are however only active at low tide. In this system the higher waves maintain a surf right across the systems as the tide rises and falls, but only during the low tide turn-around is there sufficient time for the cellular surf zone processes to imprint themselves on the morphology, producing surf zone topography essentially identical to the wave-dominated intermediate counterparts. However, there is no associated shoreline rhythmic forms, as the tide-modified surf zone is detached from the shoreline by as much as a few hundred meters (**Figure 11**). At mid to high tide the low tide

Figure 10 Reflective high tide beach and wide low tide terrace, Embleton Bay, Northumberland (A.D. Short).

Figure 11 Nine Mile Beach, Queensland, showing a dye-highlighted low tide rip current, the 100 m wide intertidal zone with a low swash ridge, and the linear high tide reflective beach (right) (A.D. Short).

Figure 12 Rhossili Beach in Wales is an exposed high-energy tide-modified beach shown here at low tide. Note the wide, flat, featureless intertidal zone, and wide dissipative surf zone, which moves across the beach every six hours (A.D. Short).

morphology is dominated by shoaling waves as the surf zone moves rapidly shoreward.

Ultradissipative

Higher energy tide-modified beaches composed of fine sand are characterized by a wide, low gradient concave upward, flat, and featureless, beach and intertidal system (**Figures 9** and **12**). These beaches are swept by both high incident waves and their associated long waves (set up and set down), as well as shoaling waves at high tide. Even at low tide the waves cannot imprint their dissipative bar morphology on the topography. The only surface features usually present on the low tide beach are wave and swash ripples.

Tide-dominated Beach

When the RTR exceeds 15, the tide range is more than 15 times the wave height. As the maximum global tide range is about 12 m, and usually much less, this means that most tide-dominated beaches also receive low (<1 m) to very low waves, and are commonly dominated by locally generated wind waves. Tide-dominated beaches in fact represent a transition from beach to tidal flats, though they must still maintain a high tide beach. Tide-dominated beaches are characterized by a usually steep high tide beach, and a wide, low gradient ($<1^\circ$) sandy intertidal zone, which in temperate to tropical locations is usually bordered by subtidal seagrass meadows.

Beach and Sand Ridges

The beach and sand ridge type consists of a steep, reflective low-energy high tide beach, which is only active during spring high tides, and in seagrass locations is usually littered with seagrass debris. It is fronted by a low gradient sand flats which contain multiple, sinuous, shore-parallel, equally spaced, low amplitude sand ridges. On the Queensland coast the number of ridges range from one to 19 and averages seven. What causes the ridges is still not understood, and they are very different in size and spacing from the standing wave-generated multiple dissipative bars. They do, however, occur on the more exposed sand flat locations, compared to the next beach type.

Beach and Sand Flats

A beach and sand flats is just that; a very low energy periodically active high tide reflective beach, fronted by a wide flat, featureless intertidal sand flat. The only features on the sand flats are usually associated ground-water drainage from the high tide beach, and bioturbation particularly crab holes and balls.

Tidal Sand Flat

The final ‘beach’ type is the tidal sand flat, which is a beach in so far as it consists of sand and is exposed to sufficient waves to winnow out any finer sediments. It is flat and featureless; it may have irregular, discontinuous, shelly high tide beach deposits, interspersed occasionally with mangroves in tropical locations, or salt marsh in high latitudes. It is transitional between the beaches and the often muddy, tidal flats with associated inter- and supratidal flora.

Beach Modification

The above beach systems assume beaches are solely a product of the wave-tides and sediment regimes. Most beaches are, however, influenced to some degree by geological inheritance, and, depending on latitude, by temperature-controlled processes.

Geological Inheritance

The dominant physical factors modifying beaches are related to the role of what is generally termed geological inheritance, that is, pre-existing bedrock (or artificial structures) and sedimentological controls. Bedrock influences beaches as headlands, which form boundaries and determine beach length. In addition headlands and associated subaqueous substrate (reefs, rocky seabed) induce wave refraction and attenuation, which in turn influences beach shape and breaker wave height. Wave refraction around headlands and reefs will tend to produce

Figure 13 A small embayed, headland-controlled beach, with a topographically controlled rip exiting against the headland, Point Peter, South Australia (A.D. Short).

Figure 14 Frozen tundra (dark patches left), beach covered by snow and ice (center) and shore-parallel ice ridges (right); Point Lay, north Alaska (A.D. Short).

swash aligned beaches in their lee, as well as lower energy beaches. Wave attenuation over rock substrates will reduce wave energy and through breaker height influence beach type. Eroding basement rocks and cliffs can also supply sediment to the beach budget.

In energetic embayed (headland-controlled) beaches, beach systems can be classified as normal, where the headland exerts no influences, as in areas with low waves or on long beaches. On shorter beaches and during moderate waves the beaches become transitional, with normal surf zone circulation in the center, and headland-induced rips to either end. Finally in high energy situations ($Hb > 3\,m$) and on shorter beaches (< few kilometers) the entire surf zone circulation becomes cellular, meaning it is controlled by the bedrock topography, leading to large-scale megarips draining the surf zone, and often aligned against a headland (**Figure 13**).

Temperature

Frozen beaches Ocean temperature is responsible for two dramatic physical impacts on beach systems. In the high latitudes when air temperature falls below zero the beach surface freezes and when ocean temperature falls below $-4°C$ the water surface freezes. In places like the Arctic Ocean beach processes cease for several months of the year, as a frozen ocean surface and snow-covered beach negate any physical activity (**Figure 14**) other than tides. When the ice and snow finally melts, near normal beach processes return and control the long-term beach morphology.

Biotic influences In the tropics, warm water ($> 26°C$) permits the prolific growth of coral and algal reefs in suitable shallow water environments. Where these reefs lie seaward of beach systems, they lower the wave height through wave breaking and therefore lead to solely reflective beaches in their lee. The reefs also supply carbonate detritus to the beaches leading to coarse carbonate rich beach systems.

In temperate semiarid to arid shelf regions such as across southern Australia and South Africa, the prolific growth of shelf carbonate supplies the bulk of the beach sediments, leading to extensive mid-latitude carbonate coasts and beach systems.

Chemical influences Water chemistry modifies tropical beaches through the formation of beachrock, the cementation of the intertidal sand grains by carbonate cement. This commonly occurs in all

Figure 15 Three bands of beachrock at Shoal Cape, Western Australia. Note the wave breaking over the successive reefs, leading to a low energy inner beach, on an exposed high-energy coast (A.D. Short).

tropical beach locations and during beach erosion leads to exposure of the beachrock parallel to the shoreline.

On arid to temperate carbonate-rich coasts subaerial pedogenesis led to the formation of calcarenite in beach and dune systems, particularly during Pleistocene low sea levels. When these systems are subsequently drowned by rising sea level, they remain as dune or beach calcarenite, and are manifest as reefs, islands, and rocky bluffs and cliffs, all of which exert a geological influence on the shoreline (**Figure 15**).

See also

Coastal Circulation Models. Geomorphology. Sandy Beaches, Biology of. Storm Surges. Tides. Waves on Beaches.

Further Reading

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BEAKED WALES

See **SPERM WHALES AND BEAKED WHALES**

BENGUELA CURRENT

L. V. Shannon, University of Cape Town, Cape Town, South Africa

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Introduction

The Benguela, which shares its name with a town in Angola, is one of four major current systems situated at the eastern boundaries of the world oceans, and the oceanography of the region is in many respects similar to that of the Canary Current off north-west Africa, the California Current off the west coast of the USA, and the Humboldt Current off Peru and Chile. The Benguela is, however, unique in that it is bounded at both equatorward and poleward ends by warm-water systems. Eastern boundary current systems are characterized by wind-driven upwelling along the coast of cold, nutrient-rich water which supports high biological productivity.

Different interpretations exist as to what constitutes the Benguela Current, its ecosystem and its boundaries. In this article, the broader definition of the Benguela will be used and the currents and physical processes which occur in that part of the South Atlantic between 5°S and 38°S and east of the 0° meridian will be considered. This encompasses the coastal upwelling regime, the eastern part of the South Atlantic gyre, and a series of fronts and transitional zones, overlying some complex bathymetry. The continental shelf along the west coast of southern Africa is variable in width, being narrow off southern Angola, near Lüderitz in Namibia, and near Cape Town, and widest off the Orange River and in the extreme south where the Agulhas Bank protrudes polewards (**Figure 1**). The shelf-break (edge of the continental shelf) lies at depths between 200 m and 500 m, from which a steep continental slope descends to about 5000 m where it meets the abyssal plains of the Cape and Angola Basins which in turn are separated by an extensive submarine mountain chain, the Walvis Ridge (**Figure 1**).

The earliest physical measurements in the area were those necessary for the safe and efficient passage of sailing ships along the trade routes between