BEACH SYSTEMS

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Incomplete article, figures missing, complete article under development.

Beaches throughout the world consist of wave deposited sediment and lie between the base of wave activity and the limit of wave run-up or swash. The entire *beach system* includes the dry (subaerial) beach, the swash or intertidal zone, the surf zone and, beyond the breakers, the nearshore zone (Fig. 2.1). Usually only the dry beach and swash zone are clearly visible, while bars and channels are often present in the surf zone but are obscured below waves and surf, and the nearshore is always submerged. The shape of any surface is called its morphology, hence *beach morphology* refers to the shape of the beach, surf and nearshore zone (Fig. 2.2).

Figure 2.1 The beach system resides at the interface of the ocean, land and atmosphere, and is affected by all three together with input from the rich coastal biota.

BEACH MORPHOLOGY

As all beaches are composed of sediment deposited by waves, beach morphology reflects the interaction between waves of a certain height, length and direction and the available sediment; whether it be sand, cobbles or boulders, together with any other structures such as headlands, reefs and inlets.

Western Australian beaches can be very generally divided into three groups: wave-dominated, tide-modified and tide-dominated. The *wave-dominated* beaches occur along the open ocean south and southwest coasts. They are exposed to persistent ocean swell and waves and low tides (<2 m). The *tide-modified* and *tide-dominated* beaches occur in Shark Bay and in the northwest in areas of higher tide range and usually lower waves. The tide-modified beaches are usually exposed to the prevailing seas in the areas of higher tide range, while the tide-dominated are increasingly protected from waves and become increasingly dominated by the tides resulting in a mix of beach and tidal flats. The remainder of this chapter is devoted to a description of first the higher energy wave-dominated beaches, followed by the tide-modified and then the tide-dominated beaches.

Wave-dominated beaches

In two dimensions beaches consist of three zones: the subaerial beach, the surf zone and the nearshore zone, however the nature and extent of these zones vary considerably between the high wave energy beaches of the south coast and the sheltered low wave beaches of the northwest (Fig. 2.2).

Figure 2.2 Examples of two typical Western Australian beach systems. The higher energy open coast beaches (upper) consist of the dry subaerial beach above the shoreline, the surf zone containing bars, troughs and breaking waves, and the nearshore zone which extends seaward of the breaker zone out to modal wave base. Wave base is the depth to which ocean waves can move beach sands. Seaward lies the inner continental shelf. The approximate width and depth of each zone are indicated. In the more protected northwest and some larger bays (lower) the lower waves and higher tide result in a lower gradient and shallower beach, intertidal and nearshore zone, with wave base as shallow as low tide.

Subaerial beach

The *subaerial beach* is that part of the beach above sea level, which is shaped by wave run-up or swash. It starts at the shoreline and extends up the relatively steep swash zone or beach face. This may be backed by a flatter berm or cusps, which in turn may be backed by a runnel, where the swash reaches at high tide. Behind the upper limit of spring tide and/or storm swash usually lies the edge of dune vegetation. The dry beach varies in width from tens of metres on high energy wave-dominated beaches, to a few metres on very low energy tide-dominated beaches. The subaerial, or dry, beach is that part which most people go to and consider 'the beach'. However, the real beach is far more extensive, in places extending several kilometres seaward, with the subaerial beach forming the figurative 'tip of the iceberg'.

Swash or intertidal zone

On wave-dominated beaches the swash zone connects the dry beach with the surf. The swash zone is the steeper part of the shoreline across which the broken waves run up and down. As wave height decreases and tide range increases, this zone tends to become flatter and considerably wider, and is termed the intertidal zone on tide-modified to tide-dominated beaches. In areas of higher tide range it may reach several hundred metres in width.

Surf zone

The *surf zone* extends seaward of the shoreline and out to the area of wave breaking. This is one of the most dynamic places on earth. It is the zone where waves are continuously expending their energy and reshaping the seabed. It can be divided into the area of wave breaking, often underlain by a bar, and, immediately shoreward, the area of wave translation where the wave bore (white water) moves toward the shoreline, transforming along the way into surf zone currents and, at the shoreline, into swash. Surf zones are up to 500 m wide on exposed southern Western Australian wave-dominated beaches, where waves average over 2 m and break across a double bar system. They decrease in width and bar number as wave height decreases. On tide-modified beaches the usually narrow surf zone is transient with the tide, while it is usually nonexistent on tide-dominated beaches.

Nearshore zone

On wave-dominated beaches the *nearshore zone* is the most extensive part of the beach. It extends seaward from the outer breakers to the maximum depth at which average waves can mobilise beach sediment and move it shoreward. This point is called the *wave base*, referring to the base of wave activity. On the high energy southern Western Australian coast, where waves average over 2 m and commonly reach several metres, it usually lies at a depth between 30 and 50 m and may extend 1, 2 or even 3 km out to sea. It decreases in depth and width as wave height decreases. On tide-modified beaches it is usually at most a few metres deep, while on tide-dominated beaches it may terminate at low tide. The fringe of the seagrass meadows, usually a metre or less below low tide, is a good indicator of its outer limit on sheltered lower energy shores.

Three dimensional beach morphology

In three dimensions, wave-dominated beaches become more complex. This is because most beaches are not uniform alongshore, but vary in a predictable manner.

Beaches vary longshore on two scales. First, they are usually swash-aligned, meaning they are aligned parallel to the crest of the dominant wave. If the wave crest is refracted or bent as it approaches the shoreline, owing to the presence of obstacles such as reefs, rocks and headlands, then the beach will also be shaped to fit the wave crest. The overall effect of the refracting wave crests is to cause a spiral or curvature in the shape of the beach, so that the curvature increases toward the more protected end. This bending of the wave crests is called *wave refraction* (Fig. 2.3a), while the loss of wave energy and height is called *wave attenuation* (Fig. 2.3b). The decrease in wave height along the beach results in lower breakers, a narrower and shallower surf zone, a narrower and often steeper swash zone and a lower and narrower subaerial beach.

In Western Australia beaches are usually bordered by headlands and reefs. They average 1.8 km in length south of Roebuck Bay and only 530 m in length around the Kimberley, with a State average of 1.3 km, close to the Australian average of 1.37 km. As a result there is considerable opportunity for these structures to influence the size and direction of waves arriving at many beaches.

Figure 2.3 a) Wave refraction around the main reefs at Margaret River focuses the waves on the reefs with lower waves to either side; b) Wave attenuation across shallow reefs off Gnarabup Beach, result in a low energy reflective shoreline.

The second scale of longshore beach variation relates to any and all undulations on the beach and in the surf zone, usually spaced from a few metres to as much as 500 m or more on very high energy beaches. Variable longshore forms produced at this scale include regular beach cusps located in the high tide swash zone and spaced between 20 and 40 m, and all variation in rips, bars, troughs and any undulations along the beach, usually with spacing of between 200 and 500 m. These features are associated with rip circulation and are known as rip channels, crescentic and transverse bars, and megacusp horns and embayments. Each of these and its associated beach type and characteristics are described in section 2.3.

BEACH DYNAMICS

Beach dynamics refers to the dynamic interaction between the breaking waves and currents and the sediments that compose the beach. In the long term (tens to thousands of years) this interaction builds all beaches and contributes sand to form backing dune systems. It can also ultimately erode these beaches. In the shorter term (days to months), changing wave conditions produce continual changes in beach response and shape, as sand is moved onshore (beach accretion) and offshore (beach erosion), together with the associated movement of the shoreline, bars and channels.

Five factors determine the character of a beach. These are the size of the sediment, the height and length of the waves, the characteristics of any long waves present in the surf zone and the tide range. The impact of each is briefly discussed below.

Beach sediment

The size of beach sediment determines its contribution to beach dynamics. Unlike in air where all objects fall at the same speed, sediment falls through water at a speed proportional to its size. Very fine sediment, like clay, will simply not sink but stay in suspension for days or weeks, causing turbid, muddy water. Silt, sediment coarser than clay but finer than sand, takes up to two hours to settle in a laboratory cylinder (Table 2.1). As a consequence fine sediments usually stay in suspension through the energetic surf zone and tidal inlets and are carried out to sea to settle in deep water on the continental shelf.

Table 0.1 Sediment size and settling rates

Material	Size – diameter	Time to settle 1 m
clay	0.001-0.008 mm	hours to days
silt	0.008-0.063 mm	5 min to 2 hours
sand	0.063-2 mm	5 sec to 5 min
cobble	2 mm-6.4 cm	1 to 5 sec
boulder	> 6.4 cm	< 1 sec

Sand takes from a few seconds for coarse sand, to five minutes for very fine sand, to settle through 1 m of water. For this reason it is fine enough to be put into suspension by waves, yet coarse enough to settle quickly to the seabed as soon as waves stop breaking. In the energetic breaking wave environment, anything as fine or finer than very fine sand stays in continual suspension and is flushed out of the beach system into deeper, quieter water. This is why ocean beaches never consist of silts or mud. Most beaches consist of sand because it can be transported in large quantities to the coast and settle fast enough to remain in the energetic surf zone.

Twenty Western Australian beaches described in this book consist of cobbles and boulders. Cobbles and boulders require substantial wave or current energy to be lifted or moved and then settle immediately. They are therefore only rarely moved, such as during extreme storms, and then only very slowly and over short distances. Consequently, Western Australian beaches containing such coarse sediment always have a nearby source, usually an eroding cliff or bluff, while elsewhere they may lie at the mouth of gravel streams.

Depending on the nature of its sediment, each beach will inherit a number of characteristics. Firstly, the sediment will determine the mineralogy or composition of the beach. Sediment derived from the land via rivers and creeks is usually quartz sand or silica. In Western Australia, however, rivers and streams are few and most sand has been derived from the biotic detritus of the seagrass meadows and inner continental shelf and is carbonate (algal, shell detritus, etc.) as discussed in Chapter 1. Secondly, the size of the sediment will, along with waves, determine beach shape and dynamics. Fine sand produces a low gradient (1 to 3°) swash zone, wide surf zone and potentially highly mobile sand. Medium to coarse sand beaches have a steeper gradient (4 to 10°), a narrower surf zone and less mobile sand. Cobble and boulder beaches are not only very steep (> 8°), but they have no surf zone and are usually immobile. Therefore, identical waves arriving at adjacent fine, medium and coarse sand beaches will interact to produce three distinctly different beaches.

Likewise, three beaches having identical sand size, but exposed to low, medium and high waves, will have three very different beach systems. Therefore, it is not just the sand or the waves, but the interaction of both, together with long waves and tides, that determine the nature of our beaches.

Wave energy - long term

Waves are the major source of energy to build and change beaches. Seaward of the breaker zone, waves interact with the sandy seabed to stir sand into suspension and, under normal conditions, slowly move it shoreward. The wave-by-wave stirring of sand across the nearshore zone and its shoreward transport have been responsible for the delivery of all the sand that presently composes the beaches and coastal sand dunes of Western Australia.

Waves are therefore responsible for supplying the sand to build beaches. The higher the waves, the greater the depth from which they can transport sand and the faster they can transport it. Consequently, high wave energy beaches can deliver the largest volumes of sand and potentially supply sand to build the biggest dunes. Along parts of the South East and South coasts, massive amounts of up to 100,000 m^3 of sand have been transported onshore for every metre of beach. However, these same large waves can just as rapidly erode the very dynamic beaches they initially built. For this reason many high energy Western Australian beaches have left remnants of dunes on top of cliffs and bluffs, while the beaches in many cases have been completely eroded and removed.

Lower waves can only transport sand from shallow depths and at slower rates. Consequently, they build smaller barrier systems, usually delivering less than

10,000 m^3 for every metre of beach, as is typical of more sheltered parts of the open coast. However, these beaches are less dynamic, more stable and are less likely to be eroded.

Wave energy - short term

Waves are not only responsible for the long-term evolution of beaches, but also the continual changes and adjustments that take place as wave conditions vary from day to day. As noted above, a wave's first impact on a beach is felt as soon as the water is shallow enough for wave shoaling to commence, usually in less than 30 m water depth. As waves shoal and approach the break point, they undergo a rapid transformation, which results in the waves becoming slower and shorter, but higher, and ultimately breaking, as the wave crest overtakes the trough.

As waves break, they release kinetic energy, energy that may have been derived from the wind some hundreds or even thousands of kilometres away. This energy is released as turbulence, sound (the roar of the surf) and even heat. The turbulence stirs sand into suspension and carries it shoreward with the wave bore. The wave bore decreases in height shoreward, eventually collapsing into swash as it reaches the shoreline.

Breaking waves, wave bores and swash, together with unbroken and reformed waves, all contribute to a shoreward momentum in the surf zone. As these waves and currents move shoreward, much of their energy is transferred into other forms of surf zone currents, namely longshore, rip feeder and rip currents, and long waves and associated currents. The rip currents are responsible for returning the water seaward, while the long wave currents play a major role in shaping the surf zone.

It is therefore the variation in waves and sediment that produces the seemingly wide range of beaches present along the coast, ranging from the steep, narrow, protected beaches to the broad, low gradient beaches with wide surf zones, large rips and massive breakers. Yet every beach follows a predictable pattern of response, largely governed by its sediment size and prevailing wave height and length. The types of beaches that can be produced by waves and sand are discussed later.

BEACH TYPES

Beach type refers to the prevailing nature of a beach, including the waves and currents, the extent of the nearshore zone, the width and shape of the surf zone, including its bars and troughs, and the dry or subaerial beach. *Beach change* refers to the changing nature of a beach or beaches along a coast as wave, tide and sediment conditions change.

The first comprehensive classification of wave-dominated beaches was developed by the Coastal Studies Unit (CSU) at the University of Sydney in the late 1970s, followed by the first investigation of tide-dominated beaches at Cable Beach, Broome in 1980. The *wave-dominated* classification is now used internationally, wherever tide range is less than 2 m. In Australia it applies to most of the southern coast, from Fraser Island in the east around to Exmouth Peninsula in the west. In some large southern bays and gulfs, including Shark Bay, and across northern Australia, waves are lower to nonexistent and tides are generally higher, producing a different range of beach types. In the early 1990s the CSU undertook research along the central Queensland coast, which together with the earlier Broome investigations resulted in the identification of a range of *tide-modified* and *tide-dominated* beach types. Based on this work the full range of Western Australian wave-dominated, tide-modified and tide-dominated beach types is summarised in Tables 2.2 and 2.3, together with two additional types where rocks and/or reefs dominate the intertidal zone. In the following sections each of the beach types is described, together with examples and photographs of the fifteen beach types that occur along the Western Australian coast. Note this table and data relate only to the coast between Eucla and Roebuck Bay. The Kimberley coast and beaches will be covered in a later book on the beaches of Northern Australia.

Table 2.2 Western Australian (Eucla-Roebuck Bay) beach types by number and length

	Beach Type	Number	Number %	Mean (km)	SD	Total (km)	km %
	Wave-dominated						
1	Reflective	**830**	40.4	1.27	2.67	1,052.5	28.6
2	Low tide terrace	239	11.7	2.47	6.7	595.3	16.1
3	Transverse bar & rip	220	10.7	3	8.1	660	18
4	Rhythmic bar & beach	85	4.1	1.65	2.8	140	3.8
5	Longshore bar & trough	0	0		0		0
6	Dissipative	1	0.2	2	0	8.2	0.2
	Tide-modified						0
7	R+LTT	38	1.9	0.74	1.9	29.6	0.8
8	R+LT rips	0	0	0	0		0
9	Ultra dissipative	**48**	2.3	6	11.8	288	7.8
	Tide-dominated						0
10	R+sand ridges	16	0.8	2.6	0	41.6	1.1
11	R+sand flats	**329**	16	1.74	2.4	572.5	15.5
12	R+tidal flats	139	6.8	1.44	1.83	200	5.4
13	R+mud flats	4	0.2	2.2	0	10.8	0.3
	Beaches+rock/reef flats						0
14	R+rock flats	60	2.9	0.65	1.2	39	1.1
15	R+coral reef	37	1.8	1.38	1.15	49.7	1.3
		2,051	100.0			3,687.3	100

Table 2.3 Western Australian beach types by coastal regions

Beach type[1]	South East	South	Leeuwin	Central West	***Southern WA***	Carnarvon	Pilbara	Canning	***Northern WA***	**Total WA**
1	6	165	75	340	***586***	171	46	27	***244***	**830**
2	20	117	14	38	***189***	51			***51***	**240**
3	14	173	23	13	***223***					**219**
4	6	79			***85***					**85**
5										**0**
6				1	***1***					**1**
7							38	1	***39***	**39**
8										**0**
9								48	***48***	**48**
10						13	3		***16***	**16**
11	2	3		16	***21***	227	51	30	***299***	**329**
12		1			***1***	70	38	30	***134***	**139**
13								4	***4***	**4**
14	4	22	2		***27***	5	12	15	***23***	**60**
15						37			***37***	**37**

Total	52	560	114	408	***1,134***		574	188	155	***917***	**2,051**

[1] See Table 2.2 for name of beach types.

Wave-dominated beach types

Wave-dominated beaches consist of three types: reflective, intermediate or dissipative, with the intermediate having four states as indicated in Figures 2.4 and 2.5. In Western Australia all wave-dominated beach types occur on the open coast (Table 2.2).

Figure 2.4 A plan view of the dissipative, longshore bar and trough and rhythmic bar and beach beach types. As wave height increases between the rhythmic and dissipative beaches, the surf zone increases in width, rips initially increase and then are replaced by other currents, and the shoreline becomes straighter. The physical characteristics and beach and surf hazards associated with each type are indicated, as well as its beach hazard rating.

Figure 2.5 A plan view of the transverse bar and rip, low tide terrace and reflective beach types. As wave height increases between the reflective and transverse beaches, the surf zone and bar increase in width, rips form and increase in size, and the shoreline becomes crenulate. The physical characteristics and beach and surf hazards associated with each type are indicated, as well as its beach hazard rating.

Dissipative beaches (D)

Dissipative beaches occur where a combination of high waves and fine sand ensures that they have wide surf zones and usually two to occasionally three shore-parallel bars, separated by subdued troughs. The beach face is composed of fine sand and is always wide, low and firm, firm enough to support a 2WD drive car. In Western Australia there is only one fully dissipative beach at South Beach (WA 1062, Dongara) and one which grades into a multi-bar dissipative system near Point Malcolm (WA 23). Their rarity on the coast is a product of the lack of fine sand, as there are numerous beaches with waves high enough for forming this beach type, but only if the sand is also fine enough.

On dissipative beaches wave breaking begins as spilling breakers on the outer bar, which reform to break again and perhaps again, on the inner bar or bars. In this way they dissipate their energy across the surf zone, which may be up to 300-500 m wide (Fig. 2.6). This is the origin of the name 'dissipative'.

Figure 2.6 High energy dissipative beaches at a) Yokingup Bay, South East coast; and b) Shoal Point, Central West coast.

In the process of continual breaking and re-breaking across the wide surf zone, the incident or regular waves decrease in height and may be indiscernible at the shoreline. The water and energy contained in the wave at the break point is gradually transferred in crossing the surf zone to a lower frequency movement of water, called a standing wave. This is known as red shifting, where energy shifts to the lower frequency, or red end, of the energy spectrum.

At the shoreline, the standing wave is manifest as a periodic (every 60 to 120 seconds) rise in the water level (set-up), followed by a more rapid fall in the water level (set-down). As a rule of thumb, the height of the set-up is 0.3 to 0.5 times the height of the breaking waves (i.e. 1 to 1.5 m for a 3 m wave). Because the wave is standing, the water moves with the wave in a seaward direction during set-down, with velocities between 1 and 2 m/sec closer to the seabed. As the water continues to set down, the next wave is building up in the inner surf zone, often to a substantial wave bore, 1 m+ high. The bore then flows across the low beach face and continues to rise, as more water moves shoreward and sets up. This process continuously repeats itself every one to two minutes.

Because of the fine sand and the large, low frequency standing wave, the beach is planed down to a wide, low gradient, with the high tide swash reaching to the back of the beach, often leaving no dry sand to sit on at high tide.

Dissipative beach hazards

The wide surf zones and high waves associated with dissipative beaches keep most bathers to the inner swash and surf zone. They are relatively safe close inshore, though not without some surprises, while the mid to outer surf zone is only for the fittest and most experienced surfers.

Dissipative beach hazards

Most people do not venture far into dissipative surf zones as they are put off by their extremely wide surf and high outer breakers. However, if you do, this is what to watch out for:

- Outer surf zone - spilling breakers. Bigger sets break well seaward and catch surfers inside.
- Troughs - usually on/offshore currents, but chance of longshore and even rip currents, particularly under lower (< 1.5 m) wave conditions.
- Inner surf zone - watch for standing wave bores that can knock you over, fortunately shoreward. Set-down produces an often strong seaward flow, particularly closer to the sea bed, which may also drag children off their feet.
- Swash zone/beach face - this is where most bathers stay and where most get into trouble, owing to the set-up and set-down. Be aware that water level will vary considerably between set-up and set-down, and currents will reverse from onshore to offshore. At best you will be knocked over by the incoming bore, at worst you might be dragged seaward by the set-down. Children in particular are most at risk. Some young children, even babies in prams and parked cars, have been left on a seemingly safe part of the beach face, only to have a higher than usual set-up engulf them in water.
- **Summary:** Dissipative beaches are dangerous, however in Western Australia they only occur in a few locations, but are more frequent when the seas are very big, so most people don’t consider swimming, or at least not beyond the swash zone. Definitely for experienced surfers only.

Intermediate beaches

Intermediate beaches refer to those beach types that are intermediate between the lower energy reflective beaches and the highest energy dissipative beaches. They tend to require waves greater than 0.5 m and can accommodate the highest waves along the South Coast, which can average over 2 m, combined with fine to medium sand. The most obvious characteristic of intermediate beaches is the presence of a surf zone with bars and rips. On the Western Australian coast 542 (26.4%) of the beaches are intermediate. They are the most common beach type along the more exposed South East and South coasts, secondary to the reflective beaches on the Leeuwin and Central West coasts, with only 51 occurring north of Kalbarri along the Carnarvon coast, and none along the Pilbara and Canning coasts where waves are low and tides increasingly high (Table 2.3).

As intermediate beaches are produced by waves between 0.5 m and 2 m plus, they exist in a wide range of waves and associated beach conditions. For this reason, intermediate beaches are classified into four beach states. The lowest energy state is called *low tide terrace*, then as waves increase, the *transverse bar and rip*, then the *rhythmic bar and beach*, and finally the *longshore bar and trough*. Each of these beaches is briefly described below.

Longshore bar and trough (LBT)

The *longshore bar and trough* beach type does not occur as a modal inner bar type in Western Australia and will not be further discussed. For more information on this beach type see descriptions in Short (1993, 1996, 2000 and 2001).

Rhythmic bar and beach (RBB)

The *rhythmic bar and beach* type is the highest energy beach type that commonly occurs on the open coast. In all, 80 beaches, averaging 3.9 km in length, are of this type. They occupy 134 km (3.6%) of the sandy coast. These energetic beaches require two primary ingredients for their formation, relatively fine to medium sand and exposure to the high deepwater waves. They occur where waves average at least 1.5 m and sand is fine to medium (Fig. 2.7).

Figure 2.7 High energy rhythmic bar and beach, Quallup beach, South Coast. Note the large rips.

Rhythmic beaches consist of a rhythmic longshore bar that deepens where the rips cross the breakers, and in between broadens, shoals and trends shoreward. It does not, however, reach the shore, with a continuous rip feeder channel feeding the rips to either side of the bar. The shoreline is usually rhythmic with protruding megacusp horns in lee of the detached bars and commonly scarped megacusp embayments behind the rips. The surf zone may be up to 100 to 250 m wide and the bars and rips are spaced every 250 to 1,000 m alongshore.

The shallower sections of the rhythmic bar cause waves to break more heavily, with the white water flowing shoreward as a wave bore. The wave bore flows across the bar and into the backing rip feeder channel. The water from both the wave bore and the swash piles up in the rip feeder channel and starts moving sideways toward the adjacent rip embayment, which may be up to 200 m alongshore. The feeder currents are weakest where they diverge behind the centre of the bar, but pick up in speed and intensity toward the rip, particularly close to shore. In addition, the rip feeder channels deepen toward the rip.

In the adjacent rip channels, waves break less or often not at all. They may move unbroken across the rip to finally break or surge up the steeper rip embayment swash zone. The strong swash often causes slight erosion of the beach face and cuts an erosion scarp.

In the rip embayment, the backwash returning down the beach face combines with flow from the adjacent rip feeder channels. This water builds up close to shore (called wave set-up), then pulses seaward as a strong, narrow rip current. The currents pulse every 30 to 90 seconds, depending on wave conditions. The rip current accelerates with each pulse and persists with lower velocities between pulses. Rip velocities are usually less than 1 m per second (3.5 km/h), but will increase up to 2 m per second in confined channels and under higher waves.

To identify this beach type, look for the pronounced longshore beach rhythms, i.e. the shoreline is very sinuous. The shallowest, widest bars and heaviest surf lie off the protruding parts of the shore (the megacusps). Water flows off the bars, into the feeder channel, along the beach to the deeper rip embayment, then seaward in the rip current.

Rhythmic bar and beach hazards

This is the most hazardous beach type commonly occurring along the South and South East coasts. Most people are put off entering the surf by the deep longshore trough containing rips and their feeder currents. If you are swimming or surfing on a rhythmic beach, the following highlights some common hazards.

Rhythmic bar and beach hazards

- Bar - just to reach the bar requires crossing the rip feeder channel. This may be an easy wade at low tide or a difficult swim at high tide. Be very careful once the water exceeds waist depth, particularly if a current is flowing. Also, as you reach the bar, water pouring off the bar may wash you back into the channel.
- The centre of the bar is relatively shallow at low tide, but at high tide you run the risk of being washed into the rip feeder or rip channel.
- Rip feeder channel - depth varies with position and tide, both depth and velocity increase toward the rip.
- Rip - the rip channel is usually 2 to 3 m deep, with a continuous, but pulsating, rip current.
- High tide - deeper bar and channels, but weaker currents and rips.
- Low tide - waves break more heavily and may plunge dangerously, shallower bar and channels, but stronger currents and rips.
- Oblique waves - skew bar and rips alongshore.
- Higher waves - intensify wave breaking and strength of all currents.

- **Summary:** Caution is required by the young and inexperienced on rhythmic beaches, as the bar is separated from the beach by often deep channels and strong currents.

Transverse bar and rip (TBR)

The *transverse bar and rip* is the most extensive of the intermediate beach types. There are 222 TBR beaches, with a total length of 660 km (18% of coast) and an average length of 3 km. They occur primarily along the South Coast (173) on beaches composed of fine to medium sand and exposed to waves averaging between 1 and 2 m. TBR beaches receive their name from the fact that as you walk along the beach, you will see bars transverse or perpendicular to and attached to the beach, separated by deeper rip channels and currents (Fig. 2.8). The bars and rips are usually regularly spaced with a mean spacing in Western Australia of 350 m (SD = 120 m). Their surf zones range from 50 to 150 m in width.

Figure 2.8 Transverse bar and rip beaches: a) Cliffy Head; and b) Sandy Bight, note the well developed rip heads, both South Coast.

Rip currents

Beach rips: Rip currents are a relatively narrow, seaward moving stream of water flowing over or through the sand bar (Fig. 2.9). They represent a mechanism for returning water back out to sea that has been brought onshore by breaking waves. They originate close to shore as broken waves (wave bores) that flow into longshore rip feeder troughs. This water moves along the base of the beach as rip feeder currents. On normal beaches, two currents arriving from opposite directions usually converge in the rip embayment, turn and flow seaward across the bar and through the surf zone. The currents usually maintain a deeper rip feeder trough close to shore and a deeper rip channel cut into the bar and through the surf zone.

The converging currents turn, accelerate and flow seaward through the surf zone, either directly or at an angle at speeds up to 1.5 m/sec. As the confined rip current exits the surf zone and flows seaward of the outer breakers, it expands and may meander as a larger rip head. Its speed decreases and it will usually dissipate within a distance of two to three times the width of the surf zone.

Rip currents will exist in some form on ALL beaches where there is a surf zone, particularly when waves exceed 1 m. In Western Australia they are most prevalent on the higher energy South Coast beaches. State-wide 1,470 beach rips are operating on an average day along 520 km of the sandy coast (14%). They range in spacing from 200 to 700 m with a mean of 350 m (SD = 120 m). This is the largest average beach rip spacing in Australia and among the largest in the world.

Topographic rips: Headlands and reefs in the surf can induce a strong seaward flow of water, called ‘topographically controlled rip’ or ‘topo-rip’. During big seas these rips can expand to occupy an entire beach embayment and form large ‘megarips’, that is, large scale topographically controlled rips. Approximately 900 permanent topographic rips are located along the Western Australian coast, occurring primarily along the South Coast on all beaches with surf and headlands and/or surf zone reef (Fig. 2.9).

In total, Western Australia has about 2,370 beach and topographic rip systems operating on a typical day, primarily on more exposed beaches in the southern half of the state.

Figure 2.9 a) Three beach rips on Surfers Beach, Esperance; strong topographic rips at b) Ledge Point; c) Marlbemup; and d) 12 Mile Beach, east of Hopetoun.

Rip current spacing

- spacing approximately = surf zone width x 4
- in Western Australia rip spacing averages 350 m, ranges from 200 to 700 m
- also a function of beach slope, the lower the slope (hence wider the surf zone), the wider the rip spacing

TBR beaches are discontinuous alongshore as the alternation of shallow bars and deeper rip channels causes a longshore variation in the way waves break across the surf zone. On the shallower bars waves break heavily, losing much of their energy. In the deeper rip channels they will break less and possibly not at all, leaving more energy to be expended as a shorebreak at the beach face. Consequently, across the inner surf zone and at the beach face, there is an alternation of lower energy swash in lee of the bars and higher energy swash/shorebreak in lee of the rips.

This longshore variation in wave breaking and swash causes the beach to be reworked, such that slight erosion usually occurs in the embayments in lee of the rips and slight deposition in lee of the bars. This results in a rhythmic shoreline, building a few metres seaward behind the attached bars as deposition occurs and being scoured out and often scarped in lee of the rips. The rhythmic undulations are called megacusp horns (behind the bars) and embayments (behind the rips). Whenever you see such rhythmic features, which have a spacing identical to the bar and rips (200 to 700 m), you know rips are present.

The TBR surf zone has a cellular circulation pattern. Waves tend to break more on the bars and move shoreward as wave bores. This water flows both directly into the adjacent rip channel and, closer to the beach, into the rip feeder channels located at the base of the beach. The water in the rip feeder and rip channel then returns seaward in two stages. Firstly, water collects in the rip feeder channels and the inner part of the rip channel, building up a hydraulic head against the lower beach face. Once high enough, it pulses seaward as a relatively narrow accelerated flow, the rip. The water usually moves through the rip channel, out through the breakers and seaward for a distance up to twice the width of the surf zone.

The velocity of the rip currents varies tremendously. On a typical beach with waves less than 1.5 m, they peak at about 1 m per second, or 3.5 km per hour, about walking pace. However, under high waves they may double that speed. What this means is that under average conditions, a rip may carry someone out from the shore to beyond the breakers in 20 to 30 seconds. Even an Olympic swimmer going at 2 m per second would only be able to maintain their position, at best, when swimming against a strong rip.

Two other problems associated with rips and rip channels are their depth and their rippled seabed. The channel is usually 0.5 to 1 m deeper than the adjacent bar, reaching maximum depths of 3 m. Furthermore the faster seaward flowing water forms megaripples on the floor of the rip channel. These are sand ripples 1 to 2 m in length and 0.1 to 0.3 m high that slowly migrate seaward. The effect of the depth and ripples on bathers is to provide both variable water depth in the rip channels and a soft sand bottom, compared to the more compact bar. As a result, it is more difficult to maintain your footing in the rip channel for three reasons: the water is deeper, the current is stronger and the channel floor is less compact. Also, someone standing on a megaripple crest that is suddenly washed or walks into the deeper trough, may think the bottom has 'collapsed'. This may be one source of the 'collapsing sand bar' myth, an event that cannot and does not occur.

2.1.1.1 Transverse bar and rip beach hazards

Transverse beaches are one of the main reasons many Western Australian beaches have good surf. However, the good surf is also a hazard to the unwary swimmer and most drownings and rescues occur with this beach type. The shallow bars tempt people into the surf, while lying to either side are the deeper, more treacherous rip channels and currents.

Transverse bar and rip beach hazards

- Bars - the centres of the attached bars are the best place to swim. They are shallow, furthest from the rip channels and the wave bores move toward the shore.
- Rips - the rips are the cause of most surf rescues, so they are best avoided unless you are a very experienced surfer.
- Rip feeder channels - usually run along behind and to the sides of the bar, adjacent to the base of the beach. They carry water alongshore and deliver (feed) it to the seaward flowing rip current.
- In the rip embayment, the feeder currents converge and head out to sea. If you are not experienced, stay away from any channels, particularly if the water is moving and greater than waist depth.
- Children on floats must be very wary of feeder channels as they can drift from a seemingly calm, shallow, inner feeder channel, located right next to the beach, rapidly out into a strong rip current.
- Breakers - waves will break more heavily on the bar at low tide, often as dangerous plunging waves or dumpers. In the rip embayment, the shorebreak will be stronger at high tide.
- Higher waves - when waves exceed 1 to 1.5 m, both wave breaking and rip currents will intensify.
- Oblique waves - skew both the bars and rips alongshore and may make the rips more difficult to spot.
- Low tide - rip currents are more confined to the rip channel and as a result intensify at low tide.
- High tide - rip currents are weaker and may be partially replaced by a longshore current, even across the bar.
- **Summary:** It is relatively safe on the bars during low to moderate waves, but beware, as many hazards, particularly rips, lurk for the young and inexperienced. Stay on the bar/s and well away from the rips and their side feeder currents.

Low tide terrace (LTT)

Low tide terrace beaches are the lowest energy intermediate beach type and the most common intermediate type in Western Australia occurring on 239 beaches (12%) and occupying 595 km (16%) of the sandy coast. They occur on the open coast where sand is fine to medium and wave height averages between 0.5 and 1 m. They are in all coastal regions south of North West Cape, with most occurring along partly sheltered beaches of the South Coast (117) particularly where nearshore reefs and headlands lower waves to less than 1 m at the shore (Fig. 2.10).

Figure 2.10 A continuous low tide terrace beach at a) Barrens Beach; and b) Alexander Bay.

Low tide terrace beaches are characterised by a moderately steep beach face, which is joined at the low tide level to an attached bar or terrace, hence the name - low tide terrace. The bar usually extends between 20 and 50 m seaward and continues alongshore, attached to the beach. It may be flat and featureless, have a slight central crest, called a ridge, and may be cut every several tens of metres by small shallow rip channels, called *mini rips.*

At high tide when waves are less than 1 m, they may pass right over the bar and not break until the beach face, behaving much like a reflective beach. However, at spring low tide, the entire bar is usually exposed as a ridge or terrace running parallel to the beach. At this time, waves break by plunging heavily on the outer edge of the bar. At mid tide, waves usually break right across the shallow bar.

Under typical mid tide conditions, waves break across the bar and a low surf zone is produced. Waves are less than 1 m and most water appears to head toward the shore. In fact it is also returned seaward, both by reflection off the beach face and via the mini rips, even if no rip channels are present. The rips, however, are usually weak, ephemeral and shallow.

Low tide terrace hazards

Low tide terrace beaches are the least hazardous of the intermediate beaches, because of their characteristically low waves and shallow terrace. However, changing wave and tide conditions do produce a number of hazards to swimmers and surfers.

Low tide terrace beach hazards

- High tide - deep water close to shore; behaves like a reflective beach.
- Low tide - waves may plunge heavily on the outer edge of the bar, with deep water beyond. Take extreme care if body surfing or body boarding in plunging waves, as spinal injuries can result.
- Mid tide - more gently breaking waves and waist deep water, however weak mini rips return some water seaward.
- Diving - be very careful diving into the surf as the water is usually shallow and can result in head and spinal injuries.
- Higher waves - mini rips increase in strength and frequency and may be variable in location.
- Oblique waves - rips and currents are skewed and may shift along the beach, causing a longshore and seaward drag.
- Most hazardous at mid to high tide when waves exceed 1 m and are oblique to shore, such as during a strong summer sea breeze.

- **Summary:** One of the safer beach types when waves are below 1 m high, at mid to high tide. Higher waves, however, generate dumping waves, strong currents and ephemeral rips, called *side drag, side sweep* and *flash rips* by lifesavers. Use care when surfing or diving under the waves.

Reflective beaches (R)

Reflective sandy beaches lie at the lower energy end of the wave-dominated beach spectrum. They are characterised by relatively steep, narrow beaches usually composed of coarser sand. On the Western Australian open coast, sandy beaches require waves to be less than 0.5 m to be reflective. For this reason they are also found inside the entrance to bays, at the lower energy end of some ocean beaches and in lee of many of the calcarenite reefs and rock platforms that front many Bight and south west coast beaches.

In Western Australia there are 830 reflective beaches, making them the most common beach type (40%). They are however also the shortest of the beaches with a mean length of 1.27 km as they tend to form in protected pockets in lee of reefs and headlands, even along high energy sections of coast. As a result they have a total shoreline length of 1052 km, which represents only 28.5% of the sandy beach coast.

Reflective beaches are a product of both coarser sand and lower waves. Consequently, all 20 Western Australian beaches composed of gravel, cobble and boulders are always reflective, no matter what the wave height.

Reflective beaches always have a steep, narrow beach and swash zone. Beach cusps are commonly present in the upper high tide swash zone. They have no bar or surf zone as waves move unbroken to the shore, where they collapse or surge up the beach face (Fig. 2.11).

Figure 2.11 Steep, cusped reflective beaches at a) Hammer Head; and b) Little Tagon Beach.

Reflective beach morphology is a product of four factors. First, low waves will not break until they reach relatively shallow water (< 1 m); second, the coarser sand results in a steeper gradient beach (5-10^{o}) and relatively deep nearshore zone (> 1 m); third, because of the low waves and deep water, the waves do not break until they reach the base of the beach face; and finally, because the waves break at the beach face, they must expend all their remaining energy over a very short distance. Much of the energy goes into the wave swash and backwash, the rest is reflected back out to sea as a reflected wave, hence the name reflective.

The strong swash, in conjunction with the usually coarse sediment, builds a steep, high beach face. The *cusps,* which often reside on the upper part of the beach face, are a product of sub-harmonic edge waves, meaning the waves have a period twice that of the incoming wave. The edge wave period and the beach slope determine the edge wave length, which in turn determines the cusp spacing. On the Western Australian coast cusp spacing can range from 20 to 40 m.

Another interesting phenomenon of most reflective beaches is that all those containing a range of sand sizes have what is called a *beach step.* The step is always located at the base of the beach face, around the low water mark. It consists of a continuous band containing the coarsest material available, including rocks, cobbles, even boulders and often numerous shells. Because it is so coarse, its slope is very steep, hence the step-like shape. They are usually a few decimetres in height, reaching a maximum of perhaps a metre. Immediately seaward of the step, the sediments usually fine markedly and assume a lower slope.

The reason for the step is twofold. The unbroken waves sweep the coarsest sediment continuously toward the beach and the step. The same waves break by surging over the step and up the beach face. However, the swash deposits the coarsest, heaviest material first, only carrying finer sand up onto the beach, then the backwash rolls any coarse material back down the beach. The coarsest material is therefore trapped at the base of the beach face by both the incoming wave and the swash and backwash.

Reflective beach hazards

The low waves and protected locations that characterise reflective beaches usually lead to relatively safe swimming locations. However, as with any water body, particularly one with waves and currents, there are hazards present that can produce problems for swimmers and surfers.

Reflective beach hazards

- Steep, soft beach face - may be a problem for toddlers, the elderly and disabled people.
- Relatively strong swash and backwash - can knock children and unwary people off their feet.
- Step - causes a sudden drop off from shallow into deeper water.
- Deep water - absence of bar means deeper water close into shore, which can be a problem for non-swimmers and children.
- Surging waves and shorebreak - when waves exceed 0.5 m, they break increasingly heavily over the step and lower beach face. They can knock unsuspecting swimmers over. If swimming seaward of the break, swimmers may experience problems returning to shore through a high shorebreak.
- Most hazardous when waves exceed 1 m and shorebreak becomes increasingly powerful.
- Where fronted by a rock platform or reef, additional hazards are associated with the presence of the rock/reef.
- **Summary:** Low hazards under low wave conditions, so long as you can swim. Watch children as deep water is close to shore. Hazardous shorebreak and strong surging swash under high waves (> 1 m).

Determining wave-dominated beach type

The type of wave-dominated beach that occurs on the coast is a function of the modal wave height, which has a maximum of 2 m+, the wave period, which averages 12 seconds, and finally the sand size. While the wave period is essentially constant for the southern half of the state, the wave height is at a maximum along the South Coast, decreasing northward into the Bight and up the West coast (Fig. 1.15), as well as locally decreasing into more protected environments. Finally, sand size averages medium while it can range from fine to coarse sand.

Figure 2.12 provides a method for determining the predicted beach type based on these three parameters. Only the highest energy beaches, with waves averaging over 2 m, produce dissipative beaches in Western Australia. The same waves on beaches composed of slightly coarser (fine to medium) sand produce high-energy intermediate beach systems, in particular longshore bar and trough, rhythmic bar and beach and transverse bar and rip. Where waves are reduced slightly to average between 1 and 1.5 m, they form moderate energy transverse bar and rip beaches, while low tide terrace beaches occur where waves have been reduced to around 1 m and reflective beaches where waves are lowered still further to average about 0.5 m.

Figure 2.12 A plot of breaker wave height versus sediment size, together with wave period, that can be used to determine approximate Ω and beach type for high energy open coast (a) and sheltered beaches (b). To use the chart, determine the breaker wave height, period and grain size/fall velocity (mm or m/sec). Read off the wave height and grain size, then use the period to determine where the boundary of reflective/intermediate, or intermediate/dissipative beaches lies. $\Omega = 1$ along solid T lines and 6 along dashed T lines. Below the solid lines $\Omega < 1$ and the beach is reflective, above the dashed lines $\Omega > 6$ and the beach is dissipative, between the solid and dashed lines Ω is between 1 and 6 and the beach is intermediate.

TIDE-MODIFIED BEACHES

While the southern half of the state is dominated by high waves and low tides resulting in wave-dominated beaches, the opposite occurs in the northern half of the state. Waves are low in Shark Bay and north from Exmouth, while tide range increases progressively from Exmouth peaking at 9 m by Broome. As a consequence in Shark Bay and along the Pilbara and Canning coasts the beaches become increasingly tide-modified and tide-dominated. On the Western Australian coast 89 beaches (4.2%) are tide-modified and 472 (23%) tide-dominated, all but 21 occurring in the northern half of the state. They occupy a total of 1,093 km or 30% of the sandy coast.

By definition, tide-modified beaches occur when the tide range is between 3 and 15 times the wave height. Where tides remain low (i.e. 1 m or less) such as in Shark Bay, the waves must be less than 0.3 m to be considered tide-modified, while along the Pilbara and Canning coasts increasing tide range, as well as lower wind wave, produces these conditions on the open coast. Tide-modified beaches consist of three beach types - ultradissipative, reflective plus bar and rips and reflective plus low tide terrace (Fig. 2.13).

Figure 2.13 A three dimensional sketch of the three tide-modified Western Australian beaches: beach and low tide terrace, beach with low tide bars and rips, and ultradissipative.

Ultradissipative (UD)

Ultradissipative beaches occur in higher energy tide-modified locations, where the beaches are also composed of fine to very fine sand. They are characterised by a very wide (200-400 m) intertidal zone, with a low to moderate gradient high tide beach and a very low gradient to almost horizontal low tide beach. Because of the low gradient right across the beach, waves break across a relatively wide, shallow surf zone as a series of spilling breakers (Fig. 2.14). This wide, spilling surf zone dissipates the waves to the extent that they are known as 'ultradissipative' beaches. During periods of higher waves (>1 m), the surf zone can be well over 100 m wide, though still relatively shallow. There are 48 ultradissipative beaches in Western Australia all located along the Canning coast, north of Cape Keraudren, with the best example being the long Eighty Mile Beach. On these beaches the combination of tide exceeding 7 m, combined with the low westerly wind waves (~1 m) and fine sand beaches, produces the wide, low gradient ultradissipative systems. These are also the longest average beach type in the state, averaging 6 km in length and occupying 288 km (7%) of the sandy coast.

Figure 2.14 Two sections of Eighty Mile beach showing the wide, low gradient ultradissipative beach system.

Basically the fine sand induces the low gradient, while the tide range moves the higher waves backwards and forwards across the wide intertidal zone every six hours. The two act to plane down the beach, while the lack of stationarity or stability of the surf zone and shoreline precludes the formation of bars and rips.

Hazards: The major hazards associated with ultradissipative beaches are their usually higher waves, the relatively deep water off the high tide beach, the long distance from the shore to the low tide surf and the often considerable distance from the shoreline out to beyond the breakers. Currents run along the beach when waves arrive at angles, however strong rip currents are generally absent. Seaward of the breakers, however, shore parallel tide currents also increase in strength.

Reflective plus bar & rips (R+LTR)

Reflective beaches fronted by low tide bars and rips occur in similar environments to the ultradissipative, only on beaches with fine to medium sand. There are however no R+LTR beaches in Western Australia, a result of the lack of waves high enough to maintain an energetic low tide surf zone on the high tide range beaches in the north of the state.

Reflective plus low tide terrace (R+LTT)

The lowest energy tide-modified beach is the reflective high tide beach fronted by a low tide terrace. A total of 40 such beaches occur, all but two on the Pilbara coast.

At high tide, waves surge up the steep beach face. This continues as the tide falls, until the shallower water of the terrace induces wave breaking increasingly across the terrace. At low tide, waves spill over the outer edge of the terrace, with the inner portion exposed and dry during spring low tide (Fig. 2.15). If rips are present, they will cut a channel across the terrace and are only active at low tide.

Figure 2.15 Two steep high tide reflective beaches fronted by narrow low tide terraces, both in the Pilbara: a) Cape Lambert; and b) Cape Cossigny.

Hazards: This beach undergoes a marked change in morphology between high and low tide. At high tide hazards are associated with the waves surging against the steep high tide beach, together with the deeper water off the beach, while at low tide, waves spill across the broad, shallow terrace, with hazards associated with the deeper water off the terrace and the rips, if present.

TIDE-DOMINATED BEACHES

When the tide range begins to exceed the wave height by between 10 and 15 times, then the tide becomes increasingly important in the beach dynamics, at the expense of the waves. In Western Australia these conditions in Shark Bay are due to very low waves and along the Pilbara and Canning coasts to both lower waves and the increasing tide range. Basically there are four beach types - three with a high tide beach and sand flats, while the fourth is essentially a transition from sand flat to a tidal mud flat (Fig. 2.16). These 'beaches' receive sufficient wave energy to build the sandy, and often shelly, high tide beach, while wide low gradient sand flats extend seaward of the base of the high tide beach. The intertidal sand flats grade from the higher energy ridged flats, to flat featureless sand flats, to sand flats with tidal flow and drainage features, to finally mud flats, still with the high tide sand beach. Beyond these pure intertidal flats dominate with no beach.

Figure 2.16 A three dimensional sketch of three tide-dominated Western Australian beaches: beach+ridged sand flats, beach+sand flats and tidal sand/mud flats.

Beach plus sand ridges (R+SR)

High tide beaches fronted by multiple sand ridges occur on only 16 beaches primarily on the Pilbara, with three on the Canning coast. They occupy a total of 42 km of the sandy coast.

These systems usually have a moderate to steep high tide beach, with shore parallel, sinuous, low amplitude, evenly spaced sand ridges extending out across the inter- to sub-tidal sand flats (Fig. 2.17). The ridges are not to be confused with the higher relief (sand) bars of the higher energy beaches. The beach is only active at high tide when either very low waves or calms prevail. The intertidal zone and ridges are usually inactive. The exact mode of formation is unknown, though it is suspected that the ridges are active and formed during infrequent periods of higher waves acting across the intertidal ridged zone.

Figure 2.17 Low energy reflective high tide beaches fronted by ridged intertidal sand flats at: a) Cattle Well; and b) Herald Bluff, both in Shark Bay.

In Western Australia the number of ridges averages 11 and ranges from 4 to 22, but can reach 40 in other Australian locations, while the sand flats range from 300 to 1500 m in width, averaging 700 m. The ridges are very low amplitude, no more than a few centimetres to a decimetre from trough to crest and average about 50 m in spacing. They tend to parallel the coast, but can at times lie obliquely to the shore, while at other places they merge into more complex patterns.

Hazards: The major hazard with these low energy beaches is the relatively deep water off the high tide beach and, in places, associated tidal currents. Low tide is dominated by the wide, shallow to exposed ridges and sand flats.

Beach plus sand flats (R+SF)

The most common tide-dominated beach is the high tide beach fronted by very low gradient, flat, featureless sand flats (Fig. 2.18). There are 321 such beaches primarily in Shark Bay on the Carnarvon coast, as well as spread along the Central West, Pilbara and Canning coasts. In Western Australia the sand flats range from 10 to 5,000 m in width, with an average width of 1,000 m (SD=970 m). The beaches average 1.7 km in length and occupy 558 km (15%) of the sand coast.

Figure 0.18 Low energy high tide reflective beach, fronted by wide intertidal sand flats at Eagle Bluff, Shark Bay.

Hazards: The only hazards associated with these beaches are the deeper water off the high tide beach and the slight chance of tidal currents off the beach. Low tide reveals a wide, shallow to exposed tidal flat.

Beach plus tidal sand flats (R+TSF)

Tidal flats are not by definition 'beaches', however they are included here for two reasons. First, these tidal flats represent a gradation from the true high tide beaches of the above two beach types, to the mangrove vegetated tidal flats that dominate the tide-dominated sections of the coast. Secondly, a number of sand flats are labelled 'beaches' and known locally as such. The main difference between the beach+sand flats and beach+tidal sand flats is that the tidal flats may be vegetated with seagrass and even scattered mangroves. The tidal sand flats differ from the above sand flats in that tide-generated drainage channels and other subdued features imprint themselves on the flats (Fig. 2.19). There are 139 beaches of this type, all occurring in the very low energy sections of Shark Bay on the Carnarvon coast and along similar sections of the Pilbara and Canning coasts. The sand flats range from 50 to 6,000 m in width, averaging 890 m (SD=1,020 m). The beaches average 1.4 km in length and occupy 195 km (5%) of the sand coast.

Figure 2.19 Low energy high tide beach fronted by wide intertidal sand flats at a) Middle Creek and b) Port Smith, both on the Canning coast. Note the imprint of tidal flows on the flats.

Hazards: The only physical hazards associated with tidal sand flats are the deeper water over the flats at high tide, and the increased likelihood of tidal currents moving across, especially in drainage channels, or parallel to the flats and their wide distance at low tide, which increases the chance of being caught in the intertidal zone by the rising tide.

Beach plus mud flats (R+MF)

There are only four beaches with an intertidal mud flat extending seaward from the base of the sandy high tide beach, all located on the Canning coast, adjacent to river mouths (Fig. 2.20). They are similar to the tidal sand flats, with mud, rather than sand, occupying the intertidal zone.

Figure 2.20 A steep sandy high tide beach, grading abruptly into very wide low gradient intertidal mud flats, at Hearson Cove, Dampier Peninsula.

Beach plus rock flats (R+rock flats)

There are 59 beaches fronted by intertidal rock flats, about half located in the south, primarily on the South Coast, and half in the north spread along the Carnarvon, Pilbara and Canning coasts. The rock flats range from 20 to 400 m in width averaging 80 m. In each situation waves break at the edge and over the rocks, lowering waves at the shoreline, while the usually steep beach is only active at high tide (Fig. 2.21a). These are a more hazardous beach type, owing to the presence of the rocks in the sub- to intertidal zone, especially when exposed to moderate to high waves. Extreme care should be used in attempting to wade or swim off such a beach.

Beach plus coral reef (R+coral reef)

There are 37 beaches fronted by fringing coral reefs. They are all located along the Ningaloo Reef system on the Carnarvon coast. The reefs extend seaward from the base of the high tide beach (Fig. 2.21b), which is usually steep and composed of coral and shell debris. The reef flats average 1,400 m in width (SD=1,200 m) and substantially lower waves at the shore, even at high tide, with no waves reaching the beach at low tide. While waves are usually low at the shore, care should be taken in wading or swimming off these beaches owing to the irregular and often sharp coral surface.

Figure 2.21 a) High tide sandy beach and rock flats at Cape Bossut; and b) fringing coral reef at Maggies Reef, Ningaloo reef.

CALCARENITE

Calcarenite is a lithified (cemented) sand composed predominantly of calcareous material. The ‘calc’ stands for the calcareous and ‘arenite’ means sand. The Western Australian coast is dominated by two types of calcarenite - aeolian or dune calcarenite, when sand dunes have been cemented, commonly called *dunerock* (Fig. 2.22a), and beach calcarenite, where the intertidal beach has been cemented, commonly called *beachrock* (Fig. 2.22b).

Figure 2.22 a) One hundred metre high cliffs composed of multiple layers of dune calcarenite, Zuytdorp Cliffs; b) shore parallel beachrock reef causing heavy wave breaking and a backing more protected lagoon at Munglinup Beach.

When calcareous rich dune sands are exposed to long periods (thousands of years) of pedogenesis (soil forming processes), the sand can undergo transformation into massive calcrete, normally within 1 m of the surface. When this occurs, the original sand grains and structures are no longer present. Below this surface the sand undergoes partial cementation, which leaves the individual grains and structures visible, though cemented. In addition, towards the surface the vegetation interacts with the sand to produce a range of lithocasts (limestone cast around a trunk or root) and lithoskels (limestone cast inside a trunk or root). What all this means is that if the lithified beach and dune are subsequently exposed to wave attack, much will remain as a resilient rock or reef structure, which exerts considerable influence on the present coast.

Calcarenite occurs around the entire Western Australian coast and in places dominates the shoreline and inner shelf. It is prolific along the South East coast, particularly in the Bight where it helps lower waves along the shore between Eucla and Twilight Cove. It occurs sporadically along the South Coast, while it dominates the Leeuwin coast, where it occurs offshore as reefs and onshore as massive dune calcarenite, within which the cave systems have evolved.

Along the Central West coast it dominates the inner shelf occurring as submerged shore parallel Pleistocene barriers which form reefs, and occasionally as islands, including Rottnest Island, as well as forming many low headlands. The reefs and islands are responsible for the lower wave conditions along much of this coast. Dune calcarenite dominates the Carnarvon Coast forming the massive Zuytdorp Cliffs together with Dirk Hartog, Doore and Bernier islands, and outcrops along much of the shore between Lake MacLeod and North West Cape. On the Pilbara and Canning coasts it occurs as the core of many of the Pleistocene barrier islands and systems, that form and/or back sections of the modern coast.

LARGER SCALE BEACH SYSTEMS

The beach systems described above are all part of larger scale beach and barrier systems, the barriers including backing beach and foredune ridges and, in places, sand dunes, as well as adjoining tidal creeks and inlets and headlands and reefs. Figure 2.23 provides a schematic overview of the typical arrangement of some of these beach and associated barrier systems. In general the lowest energy systems receive low waves and are backed by low beach ridge plains, as in parts of Shark Bay (Fig. 2.24a). Moderate energy systems are backed by prograding foredune ridge plains. Such plains occur on many sandy forelands along the Central West coast (Fig. 2.24b). Moderate to higher energy beaches tend to have backing blowouts and parabolic dunes, as is common along much of the coast (Fig. 2.24c), while the highest energy stems are backed by massive dune transgression, as along the South Coast's Warren Beach (Fig. 2.24d).

Figure 0.23 Schematic cross-section of typical low, moderate and high energy Western Australia beach-dune-barrier systems. As wave height increases the width and depth of the surf and nearshore zone increase, as do the size and instability of the backing dune systems.

Figure 2.24 Dune types a) Foredune ridges overrun by some vegetated parabolics, Kangaroo Pt; b) Well developed active parabolic dune, Ronsard Bay; c) Transverse dunes, Cape Keraudren; d) Active sand ramp and clifftop dune, Red Bluff; e) Massive dune fields, Point Jedacorrudup (S 5); and f) Massive dune sheet including sand ramp and clifftop dunes, Eucla.