iv) Ridge and Runnel or Low Tide Terrace

This beach exhibits the lowest energy of the intermediate states and forms by continued shoreward migration of the bars of the previous state. This state may also occur due to the erosion of a reflective beach, thus initiating the formation of a *low tide terrace* feature. A low tide terrace causes smaller waves to break when the water is low. At this time, weak rip circulation may occur in the mostly infilled channels. At high tide, however, the small waves "miss" the terrace bar and surge directly onto the beach face. This creates high tide cusps and fully reflective conditions at this level of the shore (Fig. 1.2f).

Intermediate beaches are the most dynamic of the beach states in terms of sediment exchange between the three beach sections (sub-aerial, surf-zone and near shore). They show degrees of both reflective and dissipative processes with rip action additionally affecting sediment distribution. Variability across and along shore is characteristic of the bar-rip topography, while temporal variability is a result of varying wave conditions with weather (and the subsequent relocation of bars and rip channels). Nevertheless, it is unlikely that any one beach would show a complete temporal transition from a dissipative to reflective state. Mega-rips may drain an entire intermediate beach system and dissipative states may form rapidly during large storms; however, movement towards a reflective state during periods of calm is gradual (McGwynne and McLachlan, 1992).

1.1.4 The swash

The term *swash* refers to the body of water that runs up and down the beach once a wave has broken on the shore. It is of great importance in beach intertidal systems both physically and ecologically. Physically, it affects the position of the *effluent line*. This is the level of the shore which divides saturated and unsaturated sand (McArdle and McLachlan, 1991). Swash water filtration through the sediments can only occur above the effluent line where the sand is penetrable.

Different beach types harbour different swash climates in terms of total upwash distance as a proportion of intertidal distance: this may range from 125% on reflective beaches to less than 10% on dissipative beaches. The number of effluent line crossings thus increases with reflectivity. The effluent lines of reflective beaches are usually low on the shore as a result of the coarse grains and steep slope. Consequently, large volumes of water can filter through these systems (McLachlan, 1979; Mclachlan *et al.*, 1985). Dissipative beaches hold the opposite conditions - the flat slopes and fine sands tending to remain water logged (McLachlan, 1989; McArdle and McLachlan, 1991). The swash climates associated with each beach morph are thus closely connected with the conditions of the sand body as an environment.

1.1.5 The effect of tides on beach morphodynamics

Values of the dimensionless fall velocity (Ω) have afforded a reasonable correlation with beach state. However, recent research shows this to be the case only in environments where the range of the tide is small (Masselink, 1993). Tide ranges for beaches have been classified as being micro- (<2m), meso- (2-4m) or macrotidal (>4m). Thus reflective→dissipative beach models alone cannot account for every beach state encountered.

Beach systems contain three zones of interactive wave processes: a) a *wave-shoaling* zone seaward of the breaker point; b) an energetic *surf-zone* of breaking waves; and c) the *swash* zone where final wave dissipation occurs. These three wave bands shift with tide - the tidal range determining the scale of daily movement of the boundaries (Short, 1996). Micro-tidal systems are assumed to be wave dominated, with a tidal range small enough to play a negligible part in determining beach morphology. The zones of shoaling, surf and swash are therefore assumed to be stationary and typified by Ω. On meso- or macro-tidal beaches the situation is not as elementary.

a) Relative Tide Range (RTR)

Tides play an indirect role in sediment transport and related changes in beach morphology. Primarily, tidal action alternatively exposes and submerges a large portion (if not all) of the sub-aerial beach and inner surf-zone. The net result of this is to retard the rate at which sediment transport and other morphological processes take place. During a meso- or macro-tidal cycle, the positions of the swash zone, surf-zone and shoaling waves are moved to an extent that affects the intertidal profile (Masselink and Short, 1993). The most important factor herein is thus the *tidal range*.

Elevated tidal energy increases the dissipative nature of beaches by inhibiting the effect of ocean swells. In order to account for this Masselink and Short (1993) developed another paradigm of beach types which clarifies the role of the tides. This model classifies beaches along two axes: i) the Dimensionless fall velocity - used as an index of the dissipativeness of the surf-zone; and ii) the *Relative Tide Range* (RTR) - indicating the importance of tidal water movements and shoaling wave processes in mobilising sediment (Fig. 1.3). Relative Tide Range is the ratio of wave height to tidal reach and is expressed by:

$$RTR = TR/Hb \qquad (2)$$

[TR= mean spring tide range (m), Hb= breaker height (m)]

Small Relative Tide Range (<2) indicates the predominance of swash and surf-zone processes on the sub-aerial beach. Beaches with a large RTR (>5) are dominated intertidally by shoaling waves. Thus, in terms of dissipativeness of the system, beach morphologies in response to tide seem dependant on the interaction between wave height and tide range, rather than on one of these parameters alone (Masselink and Short, 1993)(Fig. 1.3).

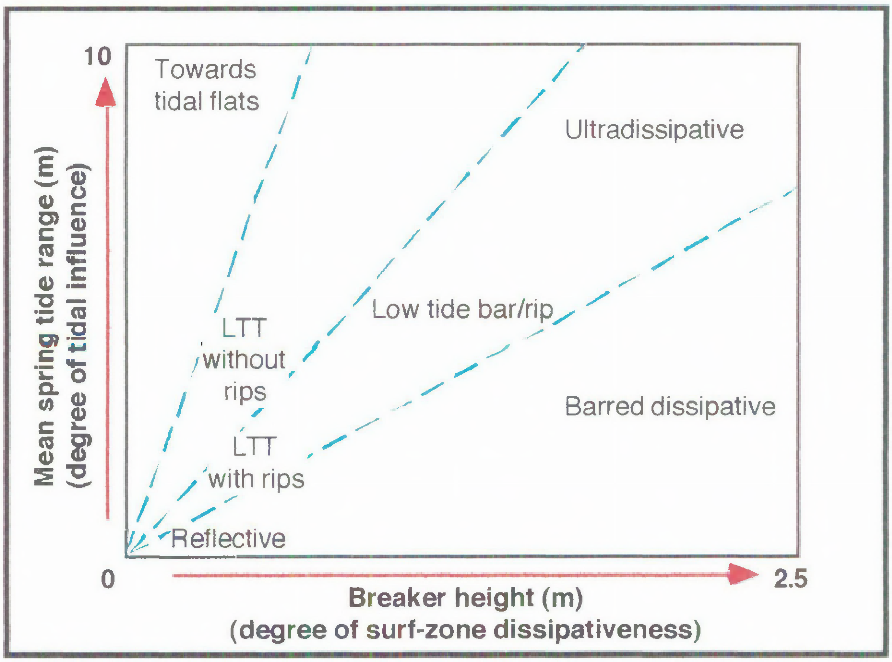

Figure 1.3: General relationship of all tidal beach types. Note that the boundaries of the beach types will shift with changes in wave period and sediment size. (LTT = Low Tide Terrace)
[After Short, 1996]

In beach morphodynamics, the three microtidal beach types (Reflective, Intermediate and Dissipative) directly apply when RTR<3. When RTR=3-7 low energy beaches (ie. the equivalent of microtidal reflective beaches) begin as a high-tide reflective beach fronted by a *low tide terrace with rips*. As tide range increases, rips are eliminated and the system moves towards a *tidal flat* (y-axis,Fig. 1.3).

As Ω increases (RTR remaining 3-7), the arrangement tends towards a wide beach with an intermediate low tide area. Following this, when $\Omega>5$, a barred dissipative beach occurs (x-axis, Fig. 1.3).

When RTR=7-15 the lower energy beaches have a reflective high tide beach and a wide low tide terrace. Where the high-tide beach is steep, the break in slope is usually at the effluent line and is obvious by a brusque change to finer sediment. Tidally dominated beaches with $\Omega>2$ are all low gradient and ultradissipative. When RTR>15 beaches become increasingly tide dominated and tend towards tidal sand flats (Short, 1996). Beyond tidal flats the sediment is very fine and stable enough to support plant life. Thus the spectrum of sandy beach types ends as a saltwater mangrove habitat is born.

b) Tidal sand flats

Like wave dominated beaches, intertidal flats are accumulations of sediment deposited by water flow. The effect of sea-driven waves, however, is greatly reduced and transport and deposition of sediment occurs mainly by means of tidal current systems. Tidal current velocities are low so the sediment on sand flats is fine and relatively stable. The profile is, as their name suggests, broad and almost horizontally level with no abrupt increase in gradient on the upper shore (De Vreis Klein, 1985). Consistently low wave height combined with large tidal range is critical in the formation of an exposed sand flat (Short, 1996)(Fig. 1.3). Exposed intertidal sand flats are the dissipative limit of this study even though there may be a further continuum into mudflats and exposed mangrove systems.

c) The Beach State Index (BSI)

Combining the effects of RTR and Ω, McLachlan et al (1993) have formulated a useful single archetype to numerically classify this entire range of beach morphodynamic states. This index is called the Beach State Index (BSI) and is expressed by:

$$\mathbf{BSI= \log([Hb.M/Ws.T.E]+1)} \tag{3}$$

(where M is the maximum tidal range of the beach in question and E is the maximum theoretical equilibrium tide for the earth covered in water [E=0.8]). The formula can also be translated to:

$$\mathbf{BSI= \log ([\Omega.tide/0.8]+1)} \tag{4}$$

Using the BSI, beaches can be categorised as follows (McLachlan et al, 1993):

< 0.5 = reflective beaches
0.5-1.0 = low to medium energy intermediate beaches
1.0-1.5 = High energy intermediate to dissipative beaches
1.5-2.0 = fully dissipative beaches
> 2.0 = ultradissipative macrotidal beaches/tidal sand flats
(refer also Fig. 1.3).

McLachlan *et al.* (1996) have suggested multiplying the above values by 5 to form a 10-point index; however, this study will use the original values.

1.1.6 Other morphodynamic influences

Recent research has improved understanding of the effects of multiple bars and embayments on morphodynamic characterisation of a beach (Short, 1996):

a) Bars.

A bar is a submerged bank of sand built on the seafloor in shallow water by wave action (Short and Hesp, 1984). They are seen as relatively shallow stretches of sand in the surf-zone on which a wave may break. Bars may be attached or detached from the subaerial beach and can form a *longshore bar* (parallel to the beach) or *transverse bar* (perpendicular to or angled towards the shore) (Short, 1993). The number of bars present in a given beach system will generally decrease as the gradient of the beach face and/or wave period increases. Because long wave periods extend into deep water where gradients are too steep for bar formation, sand bars are most likely to form in beach systems where the wave period is short. Bars increase the dissipativeness of the beach system by causing an increase in the number of breaking waves in the surf-zone.

b) Degree of embayment

Headlands, rocks and reef structures will influence the beach system through their effects on wave refraction and by their limits on the development of longshore currents and rips (Short, 1996). On beaches with widely spaced headlands, the surf-zone circulation is only affected in proximity to these outcrops with normal circulation in between. Where headlands are close together, cellular circulation causes a dominance of longshore flow with powerful seaward mega-rips (Short, 1996); these facilitating beach erosion. Degree of embayment thus influences the transport of sediments, nutrients and organisms in the beach system.

1.2 The macrofauna of sandy beaches

1.2.1 What is macrofauna?

Unlike rocky shore environments which more-or-less provide only a two dimensional habitat, soft sediments offer truly three dimensions. Beach sands also provide three environments for potential colonisation by fauna:

i) The two dimensional surface of each sand grain - These tiny surface areas are occupied by bacteria, ciliates, amoebas, foraminiferidans and other microbes (including microscopic flora) which obtain nutrients from materials percolated through the sand via wave and tidal water movement. These fauna are collectively known as *microfauna*.

ii) The porous network of the sand body - This constitutes the actual spaces between the sand grains. Many phyla have evolved numerous small and mostly vermiform animals to inhabit this interstitial environment. These are known as the *meiofauna* (middle animals).

iii) The complete sand body - Animals that are too large to dwell within beach sand interstices inhabit the sediments via the fabrication of burrows. These large tunnelling forms are jointly called the *macrofauna*.

The species of organisms dwelling in the above environments are specifically adapted to be there. However, macrofauna, meiofauna and microfauna are not simply size classes. These groups have been shown to comprise distinct ecological and possibly evolutionary units (McLachlan, 1977; Warwick, 1984). Because of the diversity of life-history features across the size spectrum, it seems that there is not one single body size most advantageous for sand-dwelling metazoans. Rather, there is a particular body size at which meiofaunal traits can be most optimised and another for macrofaunal traits (Fig. 1.4). Fewer species of a size away from the particular optima are able to exist in the confines of the relevant surrounds (Warwick, 1984).

One exception to this is the larvae of macrofaunal organisms. These may spend their early growth phases in the meiofaunal size class and hence utilise the interstitial environment for at least some of their life history. These larvae are considered *temporary meiofauna*.. Though temporary meiofauna is chiefly a size class, it seems the body sizes of these individuals are limited; they fall into the gap between adult meiofaunal and macrofaunal size class distributions (Fig. 1.4). It is likely that by remaining in the plankton until a slightly larger size, macrofaunal larvae avoid prolonged competition for resources with the highly efficient meiofauna (Warwick, 1984).

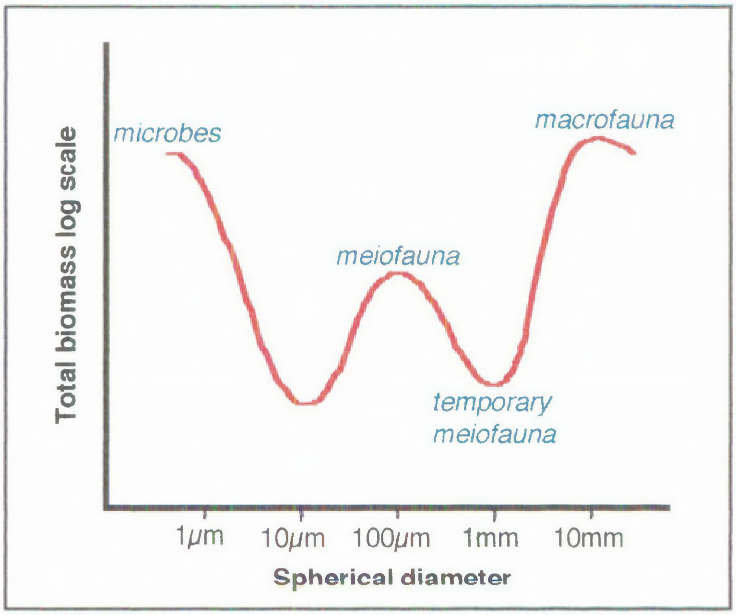

Figure 1.4: **Size distribution of beach sand organisms**
[after Warwick (1984); Brown and McLachlan (1990)]

This study focuses on adult macrofauna which are usually 1mm or larger (Fig. 1.4 and also chapter 2.1).

1.2.2 Members of beach macrofauna

"In no other region of the biosphere does it appear that purely physical factors of the environment exercise so profound an influence upon living forms as on the seashore" (Bruce, 1928). As illustrated by their morphodynamics, sandy beaches provide an environment of high physical stress and continued change. Consequently, beach fauna are often relatively impoverished (Ansari *et al.*, 1984).

Nevertheless, beach macrofauna can be a diverse group consisting of a wide range of invertebrate animals. Crustaceans, polychaete worms and molluscs are usually the dominant groups. Typical sandy beach crustaceans may include various crabs, mantis shrimps, mysid shrimps, ghost shrimps, prawns, amphipods and isopods. Sandy beach molluscs include varieties of both gastropods and bivalves. Polychaetes are the major group of worms, joined by oligochaetes and nemerteans. A number of insects are also common in/on sandy beaches - especially towards the terrestrial limit.

Though likely to be present towards tidal flat extremes, less typical animals of sandy shores include echinoderms (such as sand dollars, heart urchins and adapted starfish) and cnidarians (burrowing anemones).

1.2.3 Adaptations by macrofauna to sandy beach life

Collectively, sandy beach macrofaunal animals show adaptations and features which are directed by cycles of environmental conditions that are possibly more complex than those faced in any other system. The intertidal beach environment is "predictably unpredictable" and individuals which can exploit the constant changes will be at an advantage (Jacobs, 1996). Sand beach dwellers exhibit remarkable physiological and behavioural plasticity in order to react appropriately to changing conditions and survive (Brown, 1983;1996).

a) General characteristics of beach fauna

One of the main features of beaches as habitats is the lack of permanence of the substrate. Waves and tides constantly churn and deposit the sand while the intertidal area is alternatively submerged and exposed. Thus principal characteristics of macrofauna as a whole are great mobility and/or the ability to burrow rapidly. This is especially the case on wave dominant beaches which are subject to the most harsh intertidal climates: the more motile an animal, the faster it can burrow and the more its behaviour may override the physical forces operating on the beach face (McLachlan, 1988). No truly sedentary macrofaunal animals have been discovered on wave-dominated beaches.

Several intertidal beach species have the ability to regenerate limbs or other body extremities. This is of particular significance in light of potential predation by fishes and birds (Brown, 1983) and the often turbulent nature of the surrounding sediment. Living beneath the sand surface, many beach animals also exhibit reduced eyes or eyes positioned on the end of slender stalks.

There are few specialised feeders in beach sands. Opportunistic foraging is common, some species feeding in more than one way depending on the nature of the food available (Jones and Short, 1995). As a physiological and behavioural adaptation to a highly erratic food supply, many species are capable of scavenging and filter-feeding. Filter-feeding gives the ability to utilise the more constant particulate detritus and dissolved organic matter which is percolated through the sand from the sea.

Tidal migrations of fauna up and down the beach face are so common that the phenomenon may be considered characteristic of this type of ecosystem (Brown, 1983). Many species move across shore in order to remain in the swash zone with changes in tidal height. This may be be associated with maximising food resources and avoiding predators. Tidal migrations may be regulated by: endogenous activity rhythms; position of the sun/moon; and sensitivity to water flow, current direction, thixotropy and mechanical disturbance of the sand by water movement (McLachlan, 1988; Naylor and Rejeki, 1996). Tidal activities may also affect the distribution of animals on a sandy beach at any given time (see chapter 11, Part C).

In response to differing shore environments, members of the same species may exhibit great plasticity of behaviour in their positions on the beach face (Brown, 1996). The ability to effect such behavioural modifications is necessary in order to avoid being swept out to sea or stranded at high tide level during periods of increased wave action (eg. storms). Similarly, many organisms orientate themselves according to the slope of the beach and direction of currents for feeding (Hedgpeth, 1957).

A poorly understood aspect of the ecophysiology of beach macrofauna is the mechanisms underlying the apparently gregarious behaviour in many beach species (Brown, 1983). Species tend to aggregate and form patchy distributions along the shore. This is frustrating for researchers trying to obtain precise estimates for populations and other macrofaunal community parameters (see section 2.2). The explanations for this apparent behaviour may lie in feeding or breeding aggregations and/or from convergence of water currents.

b) Animal-sediment bonds

A general increase in animal abundance with decreasing grain size has been accepted by beach ecologists for a considerable time (Gray, 1974; Withers, 1977). Changes in beach macrofaunal communities[13] with average grain size have been linked to the associated modifications in porosity, permeability and beach slope; including the subsequent effects on water and nutrient retention. These factors in turn may limit body size, burrowing rates and other functions in a variety of species, causing populations to be present or absent depending on the sediment regime (McLachlan, 1996).

Community diversity and abundance have also been shown to increase with decreasing sediment evenness[14] (Kay and Knights, 1975); possibly due to an increase in number of local micro-habitats. Grain size characteristics may also be important in the recruitment of macrofauna juveniles (Lastra and McLachlan, 1996).

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[13] The sandy beach **macrofaunal community** is here defined as the group of populations of different macrofaunal species inhabiting the area between the high and low tide marks.

[14] Sediment **evenness** refers to the degree of sorting of the sediment (ie. the distribution of the grains amongst various size classes). Even sediment is well sorted and comprises a high proportion of similarly sized grains.

Sediment stability has been shown to affect beach macrofauna so that faunal evidence may be used as a guide to the temporal parmanence of the beach environment (Allen and Moore, 1987). Macrofaunal community structure has also been linked to the degree of sediment erosion associated with exposure (Ong and Krishnan, 1995). Indeed, recently macrofaunal species number, abundance and biomass has been shown to be significantly related to beach morphology (see section 1.3.2) with sediment a major parameter in defining the relevant beach states (refer sections 1.1.3 and 1.1.5).

Interestingly, in return, benthic organisms of an intertidal sandflat may also influence the mass properties of their encompassing sediment via *bioturbation* (Grant, 1983). Bioturbation includes the animal effects of pelletisation, tube construction and mucus on the erodibility of the sediment, as well as shore reworking by feeding and burrowing activities. The constitution of macrofaunal communities may thus be altered as a result of the effects of these animals on their own surrounds (Gray, 1974). On exposed wave-dominant beaches, however, this effect would probably be negligible due to the over-riding forces of the water acting on the available sand - as demonstrated by the lack of animals inhabiting permanent burrows.

c) Seasonality

Variations in macrofaunal community structure may result from differing reproductive and movement cycles among species populations at different times of year. Communities dominated numerically by seasonally reproductive species will vary systematically depending on their recruitment and mortality trends (Boesch, 1973; Holland and Polgar, 1976). This is coupled to any effects of seasonal weather patterns on the morphology of the beach (Calliari *et al.,* 1996). Dramatic fluctuations within individual species populations or as a whole community may also occur over long periods (Brown and McLachlan, 1990; Bamber, 1993). Generally, short term variations are thought to result mainly from factors acting on small spatial scales (eg. localised water movements and disturbances) while factors acting at large spatial scales are responsible for long term changes (Morrisey *et al.,* 1992).

Change in season, by its very nature, should have a cyclic effect on the structure of macrofaunal communities (Boesch, 1973). This cyclic effect has been demonstrated by Buchanan *et al.* (1973) who showed that, although abundances differed from year to year, the general annual features of a macrofaunal community were the same. That is, each year the total number of macrofauna individuals and biomass began to increase in late spring and early summer, to peak in late summer and then fall to a minimum in winter. Dexter (1979) also noted a marked reduction in individuals on Carribean beaches during the early dry season (winter), with an overall community increase at the