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Sheltered Sandy Beaches of Southwestern Australia

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ABSTRACT

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Morphodynamic classifications of sandy beaches have been established for open-ocean, wave-dominated environments. However, many natural sandy beaches exist in embayments, or are landward of protective reefs, where they are sheltered from the full effects of ocean waves. It is therefore appropriate to question whether such low-energy beaches can be related to conceptual models of beach hierarchies, and to examine whether they have identifiable morphodynamic signatures.

Surveys were conducted of the nearshore morphology and dynamics on over fifty beaches on the microtidal coast of Southwestern Australia, between Cape Arid on the South and Geraldton on the West Coast. In most instances, surveys were conducted on beaches that were sheltered by their aspect and/or the presence of offshore reefs. The remaining surveys were conducted on wave-dominated beaches in order to provide a link to the existing morphodynamic models.

Descriptions of beach morphology, determined from the surveys, were subjected to a cluster analysis to establish groupings of similar morphologic types. This analysis provided a six-fold classification of beach morphologies and indicated a clear separation between the low- and high-energy beach morphologies on the basis of the overall scale of the nearshore profiles. Four low-energy morphotypes were distinguished. These are essentially planar and characterised by the absence of either nearshore bars or other rhythmic features. However, the low-energy morphotypes may be discriminated by variations in beach slope and curvature.

Canonical variate analysis was conducted to examine the discrimination of the six morphotypes on the basis of their sedimentary and dynamic characteristics. This analysis indicated consistent sedimentologic differences between the morphotypes, despite moderate overlapping between several of the beach forms. The variation accords with expectations that flatter beaches tend to have finer sediments. Discrimination between the morphotypes on the basis of their dynamic variables was less revealing. This raises questions of misfitting between form and process during the surveys and may indicate the importance of storm events in the formation of these low-energy morphotypes.

ADDITIONAL INDEX WORDS: *Morphodynamics, micro-tidal beaches, low-wave environments, inheritance, sheltering, Southwestern Australia, sandy beaches.*

INTRODUCTION

Since the late 1960's there has been a dramatic and extensive increase in field, laboratory and theoretical research dealing with three-dimensional inshore and beach dynamics. Recent reviews of this work have been reported by BEARDSLEY *et al.* (1987), DEAN (1987), WIEGEL (1988), NEARSHORE PROCESSES WORKSHOP (1990) and PLOEG (1991). Despite the breadth of research conducted on sandy beaches dominated by moderate to high wave (WRIGHT and SHORT, 1984; SUNAMARA, 1989; LIPPMAN and HOLMAN, 1990) and high tidal (WRIGHT *et al* 1982; SHORT, 1991; MASSELINK and SHORT, 1993) conditions, relatively little detailed research has been undertaken on the morphology and dynamics of sheltered beaches which experience very low wave energies. Notable exceptions include the work of NORDSTROM (1977, 1992), OWENS (1977), and NORDSTROM and JACKSON (1992). Their research demonstrates that beaches which experience low wave conditions respond very differently to changing wave conditions than beaches exposed to higher wave activity, although NORDSTROM (1992) notes that the morphologies and dynamics of micro-tidal sandy beaches developed in low-energy environments have not been examined in detail.

For the purposes of this investigation, wave energy is classified as being low when the annual significant breaker height is less than 1.0 m and high when it exceeds 2.0 m. Beaches exposed to relatively high wave energies generally undergo rapid erosion and accretion in response to storm onset and passage (NORDSTROM, 1980). Such beaches undergo a quasi-cyclic pattern of change, with phases of erosion and accretion occuring over short periods ranging from several days to weeks (OWENS, 1977; NORDSTROM, 1980). In contrast to this, sheltered beaches tend to exhibit a lower frequency response corresponding with seasonal variation in wave energy. Modal wave conditions prevailing on sheltered beaches are commonly insufficient to facilitate full beach recovery between periods of storm activity. For example, shoreward displacement of the beach profile during the storm season may

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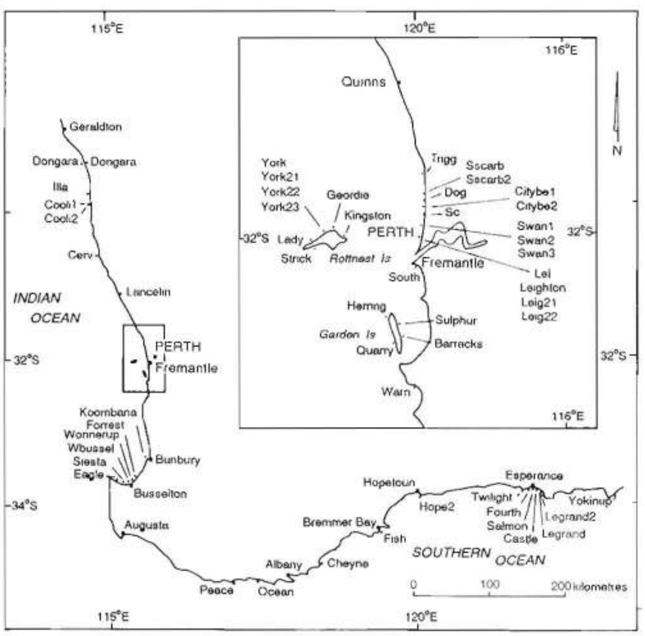


Figure 1. Regional setting and location of beach surveys.

result in cliffing of the foredunes, and recovery to prestorm conditions may only occur following a long period of queiscence (OWENS, 1977; NORDSTROM, 1980). Hence, relict or inherited morphology is often an important feature of low energy environments.

NORDSTROM (1992) and NORDSTROM and JACKSON (1992) essentially observed two types of profile response to changing wave energies on sheltered sandy beaches. Both were confined to the beachface and occurred under rising energy conditions. The first involved transfer of sediment from the upper to the lower foreshore, and resulted in development of an upwardly concave beach profile. The second involved a parallel retreat of the foreshore which was related to longshore current activity. These results raise interesting questions concerning the diversity of forms that might occur in sheltered environments, as well whether each form has an associated pattern of beach response to changing energy conditions.

Temporal variation in beach morphology and dynamics was not examined in the investigation of beaches of Southwestern Australia reported here. Rather, the two-dimensional morphology, sediments and dynamics of sandy beaches on the sheltered ocean coast of Southwestern Australia, between Cape Arid on the South and Geraldton on the West Coast (Figure 1) were surveyed to determine whether different morphologies and their particular sedimentologic and dynamic associations could be discriminated. In particular, field surveys were conducted to:

(1) describe the morphologic diversity of the beaches to determine whether beach forms characteristic of low-energy, micro-tidal conditions can be identified;
(2) examine the relationship between beach forms and their sedimentologic and dynamic characteristics; and
(3) relate the low-energy, microtidal beach types to currently available models of nearshore morphodynamics.

All beaches surveyed are situated in open-ocean environments but are sheltered from the direct impact of high energy swell, either by offshore reefs, islands or headlands or by the aspect of the beach with respect to the direction of the prevailing swell and storm waves. These two forms of sheltering are commonly combined along the coast of Southwestern Australia to result in low wave energies at the shoreline.

COASTAL PROCESSES IN SOUTHWESTERN AUSTRALIA

Recent research has emphasized the *relative*, rather than the *absolute*, amplitudes of waves and tides as it is the combined effect of wave and tide generated processes that determines the nearshore morphology (DAVIS and HAYES, 1984; DAVIS, 1991; MASSELINK and SHORT, 1993). Hence, similar coastal features may develop over a wide range of absolute tidal range or wave energy conditions if there is a balance between their respective contributions to coastal processes. However, as both the wave and tidal energy decrease the relative importance of other phenomena in controlling the nearshore morphology increases. Such phenomena include nontidal sea-level fluctuations which may arise from a variety of sources, including barometric pressure effects, seiching, shelf waves, and wind set-up and set-down. In extremely low-energy environments even boat wakes may cause observable morphologic changes (PATTIARATCHI and HEGGE, 1990: NORDSTROM, 1992).

Three oceanographic processes are of importance in controlling the morphology of sandy beaches in Southwestern Australia: tides, waves and low-frequency fluctuations in sea level. The relative importance of each of these is illustrated in Figure 2, which was computed from the observed and predicted sea-level record observed in 1991 at Fremantle and an 8 month wave record (January 1993 to August 1993) obtained in deep water off Fremantle. The results demonstrate the importance of swell as an *energy* source on this part of the coast. However, in other respects, the relative *amplitude* of tides, low-period sea-level fluctuations and waves determines the total excursion of sea level at the shore and the level at which wave energy is likely to be dissipated. Hence the amplitude of these three phenomena is of fundamental importance to the development of nearshore morphology.

Tides

DAVIES (1964) proposed a three fold classification of tidal range: microtidal (< 2.0 m), mesotidal (2.0 to 4.0 m) and macrotidal (> 4.0 m). However, several researchers have argued for the redefinition of the microtidal cutoff to 1.0 m since coasts with such low tide ranges, such as the coast of Southwestern Australia, are essentially tideless (EASTON, 1970; HAYES, 1979; and NORDSTROM, 1992). In this respect, the coastline of Southwestern Australia is microtidal and experiences mixed, predominantly diurnal tides (DEPARTMENT OF

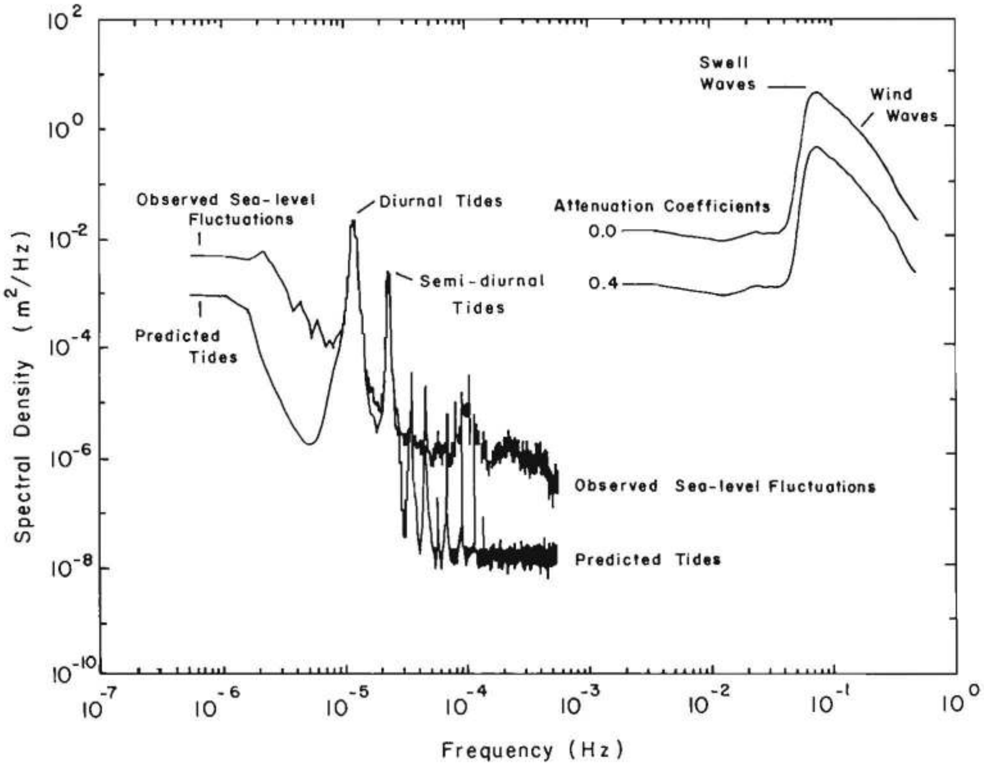


Figure 2. Spectra of sea-level energy along the coast of Southwestern Australia.

DEFENCE, 1990). Mean tidal range (MLLW to MHHW) along the coast from Geraldton to Albany is less than 0.5 m and rises to 0.7 m at Esperance in the southeast. The range of the lowest to highest astronomical tide is 1.5 m or less at all ports (DEPARTMENT OF DEFENCE, 1990) and may be compared to the extreme range of sea-level recorded, which was 2.04 m at Fremantle between 1896 and 1968 (STEEDMAN, 1977). This indicates that other processes contributing to sea-level variations may equal or exceed tidal and wave amplitudes in the region.

Low-frequency Fluctuation in Sea-level

Superimposed on the regular tidal movements are a suite of meteorologic effects which contribute to sea-level fluctuation through changes in atmospheric pressure and wind stresses. Variations in atmospheric pressure account for a considerable proportion of sea-level excursions along the coast of Southwestern Australia: 85% at Albany, between 56% and 85% at Fremantle, 43% at Geraldton and 20% at Bunbury. Hence, the small tidal signal along the Southwestern Australian coast is often overwhelmed by meteorological forces (HODGKIN and DI LOLLO, 1958; ELIOT and CLARKE, 1986). As a result, many of the low-energy beaches display a morphology that has been inherited from previous high sea-level events. In particular, processes associated with storms (ELIOT and CLARKE, 1986) and, in some instances, local sea breeze activity (PATTIARATCHI *et al.*, 1993), have lasting effects on the morphology of the upper beachface.

Passage of the prevailing synoptic-scale, anticyclonic weather systems across the coast induces continental shelf waves. They are apparent as residuals in the sea-level record after the predicted tides have been extracted from the observed sea level fluctuations. Typically, they have amplitudes in the range of 20 to 40 cm, periods of 5 to 20 days, and wavelengths of a few thousand kilometres (MYSAK, 1980; PARIWONO *et al.*, 1986). Superimposed on the shelf waves are a series of smaller amplitude and higher frequency oscillations that may be attributed to inshore seiching. Persistent seiching has been observed along the west coast between the shoreline and the submerged reef chains that parallel the coast some 5 to 10 km offshore with periods of up to 30 minutes and shore amplitudes in excess of 10 cm (ALLISON and GRASSIA, 1979; ALLISON *et al*, 1980).

Waves

The offshore wave climate of the region is dominated by a persistent, low to moderate energy wave regime, characterised by south to southwesterly swell (SILVESTER, 1976). The mean annual deep water wave height is 2.0 to 3.0 m, and the swell period ranges from 10 to 14 sec (SILVESTER, 1976; RIEDEL and TRAJER, 1978). Wave energy conditions are lowest through summer to autumn (December to May) and are high-

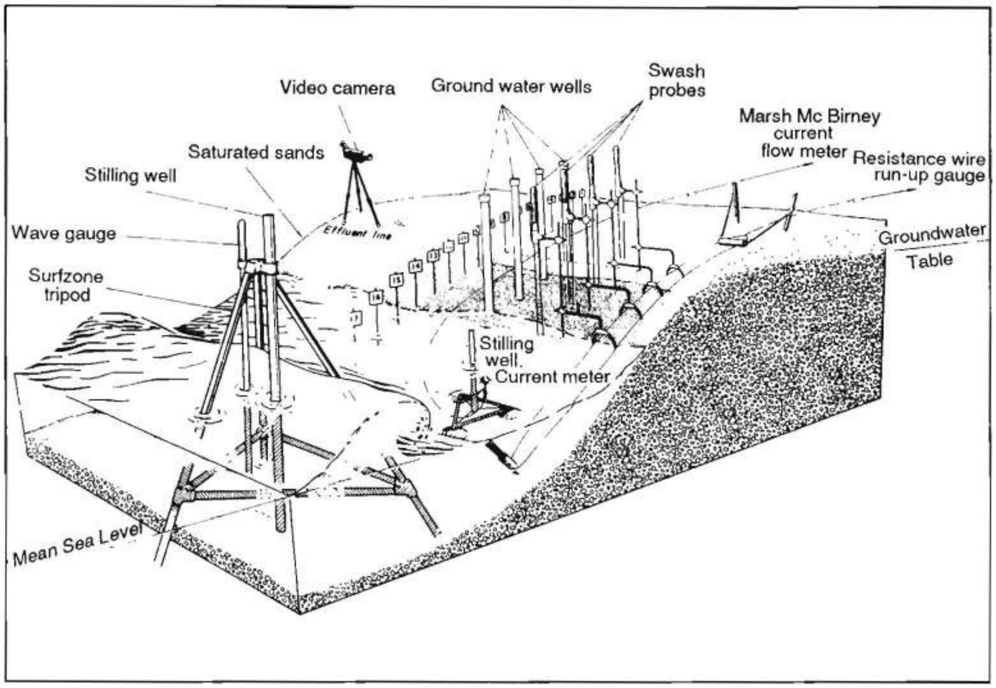


Figure 3. Typical deployment of the complete array of monitoring equipment used in the field surveys. Data obtained from the nearshore stilling wells, swash probes and groundwater wells was not used in this investigation.

est, and at their most variable, in winter to spring (June to November). Superimposed on the swell regime are waves generated by mid-latitude depressions, tropical cyclones and sea breezes. The mid-latitude depressions may generate locally significant waves from the northwest with periods ranging from 8 to 10 sec, and wave heights ranging from 1.5 to 2.5 m. The strong sea breezes of the region generate wind waves with periods of 3 to 4 sec. Under late summer to autumn conditions, the energy in wind waves generated by sea breeze activity may exceed that of the prevailing swell (PATTIARATCHI *et al.*, 1993).

Closer to shore, the inshore wave energy is often considerably attenuated by refraction and diffraction processes around reefs and headlands. This effect is particularly apparent on the west coast where an extensive reef chain runs sub-parallel to the coast. The reef system along the west coast, between Mandurah and Yanchep, attenuates an average of 39% of the offshore wave energy (Figure 2), this attenuation is greatest across the swell band (STEEDMAN 1977). Along the south coast, isolated reefs and, particularly, headlands offer local protection to the beaches but generally the attenuation is less than that occurring on the west coast.

Tides, low-period sea-level fluctuations and waves combine with the inner continental shelf topography to produce a highly variable wave regime along the coast of Southwestern Australia. On the west coast, in particular, the presence of the offshore reef system causes the alongshore distribution of wave energy to be highly sensitive to the deep water wave direction (DAVIES, 1982) and to variation in the local wind wave regime (STEEDMAN, 1977). Storm surging and seiching is also dependent on local bathymetry and the orientation of the coast with respect to the prevailing weather conditions. As a result, the beaches of the region display wide variation in their form and hence are especially appropriate for comparative studies of their morphology and dynamics.

FIELD AND LABORATORY TECHNIQUES

The traditional approach to examining and distinguishing the morphodynamic states of beaches developed under moderate to high wave conditions has been based on relatively easily observed visual features such as nearshore bars and longshore rhythmicity. The models thus developed (e.g. WRIGHT and SHORT, 1984; SUNAMURA, 1985; LIPPMANN and HOLMAN, 1990) provide significant insight into these systems. However, the challenge of low-energy beaches is to distinguish beach morphotypes where these features are not present and the differences between forms are more subtle. Hence, in the present study, exploratory multivariate techniques, including cluster analysis and canonical variate analysis, were employed.

Fifty two surveys, each of approximately 1 hour duration, were conducted on 40 unique sandy beaches along the coast of Southwestern Australia; 39 on the West and 12 on the more exposed beaches of the South Coast (Figure 1). They were selected to provide a range of wave energy, sedimentary and morphologic conditions. At each field site, an array of sampling equipment was deployed along a profile line transecting the beachface and inshore zone (Figure 3). The equipment included a resistance wire run-up gauge, Marsh-Mc-

Table 1 *Geometric variables employed to describe the morphology of the beach systems*

	Dimensions (Height/ Width)	Slope	Scale/ Curvature
Berm	●	●	
Nearshore	●	●	●
Intake zone	●		
Foreshore	●	●	●
Swash zone	●	●	●
Step	●		
Surf zone	●		
Inshore zone		●	●

Table 2. *Variables used to describe the sedimentological characteristics of the beach systems.*

	Mean	Std. Dev.	Skewness	Kurtosis
Grain size	●	●	●	●
Settling velocity	●	●		
Permeability	●			

Birney bi-directional flow meter, and a pressure/capacitance wave gauge. The morphology was established by standard survey techniques. Sediment characteristics were determined by sieving and settling tube analysis of sediment sampled from the mid-beachface. Permeability was determined in-situ on the upper beachface by using a Mariotte siphon (BOUWER, 1986). A range of dynamic variables were electronically monitored, including pre-breaking waves, cross-shore and longshore currents immediately seaward of the step or shore break position, swash motion and swash interactions on the beachface. Detailed descriptions of the field equipment and techniques are provided by HEGGE (1994).

For each beach survey, 27 variables were employed to describe the nearshore morphology (Table 1), 7 the sediments (Table 2), and 46 the extemporary dynamics (Table 3). This provided a large multivariate data set of 80 variables for each of the 51 surveys.

The survey sites were selected to examine a wide range of microtidal beaches under the low-energy conditions prevailing through mid-summer to early autumn (December to May). The beaches were chosen with specific regard to variation in modal energy levels, morphologies and sediment characteristics. In particular, beaches which were known to experience prevailing wave heights of less than 1.0 m, and in many instances less than 0.5 m for much of the year, were selected for survey. Several other surveys were conducted on beaches which experience modal conditions of moderate to high wave energy to establish continuity with previous morphodynamic research.

A visual assessment of the level of sheltering at each beach was determined from hydrographic charts in order to examine the degree of bias in sampling. In this preliminary analysis, the level of protection was denoted by a rating of 0 to 4, ranging from fully protected to fully exposed conditions. Aspect was denoted by the direction the beach faced. Beaches referred to on the outer edge and in the southern and western quadrants of the shelter plot (Figure 4) are the least sheltered, whereas beaches identified near the centre of the plot are most sheltered. The observations indicate that a broad range of beaches was represented in the sampling, with westerly facing beaches being most commonly represented.

IDENTIFICATION OF BEACH MORPHOTYPES

Beach Morphology

The surveyed profiles were divided into a series of natural segments (Figure 5), and a range of coefficients were determined to describe them (Table 1). Twelve surveys and three variables were dropped from the analysis due to incomplete data, and an empirical classification of the beach geometry was then made using cluster analysis of the remaining 24 variables and 39 beaches. Several clustering techniques were applied to the data and their results compared. For brevity, and because the results were not markedly dissimilar, only the results from Ward's minimum variance method (WARD, 1963) are reported here.

In the present analysis six clusters were determined for further interpretation because that number provided a reasonable balance between the requirements of fine scale resolution of the beach forms and data summarisation purposes. The six morphologic groups identified from the cluster analysis are geometrically consistent and describe beaches that are dominantly: concave (group 1), steep (group 2), flat (group 3), moderately concave (group 4), moderately steep (group 5) and stepped (group 6).

The group structure of the six beach forms was analysed by canonical variate analysis (ALBRECHT, 1980; EVERITT and DUNN, 1991). This technique was also employed to examine the sedimentologic and dynamic relationships between the six groups. The differences between the morphotypes may be determined from the degree of overlap of the 'core' observations of each beach type in the canonical variate space. On any particular canonical variate plot, morphotypes that were well separated, and did not overlap, may be inferred to have notably different characteristics. The same 24 geometric variables used in the cluster analysis were employed in the canonical variate analysis, and the six resulting groups were as

Table 3. *Variables used to describe the extemporary dynamics of the beach systems.*

	$\bar{x}$	sd	$Hz_{1/3}$	$Hc_{1/3}$	$Tz_{1/3}$	$Tc_{1/3}$	E_I	E_s	E_w	R_l	R_t
Waves		●	●	●	●	●	●	●	●	●	●
Cross-shore current	●	●	●	●	●	●	●	●	●	●	●
Longshore current	●	●	●	●	●	●	●	●	●		
Instantaneous shoreline	●	●	●	●	●	●	●	●	●	●	●

$\bar{x}$ = mean; sd = Standard Deviation; $Hz_{1/3}$ = significant zero down-crossing height; $Hc_{1/3}$ = significant crest-to-trough height; $Tz_{1/3}$ = significant zero down-crossing period; $Tc_{1/3}$ = significant crest-to-trough period; E_I = proportion of infragravity-band energy; E_s = proportion of swell-band energy; E_w = proportion of wind-band energy; R_l = mean run length; and R_t = mean total run

Note: In addition, five variables were employed to describe the swash interactions: No. of overtaking interactions; No. of overridding interactions; No. of suppressed interactions; No. of free interactions; and total No. of swash events

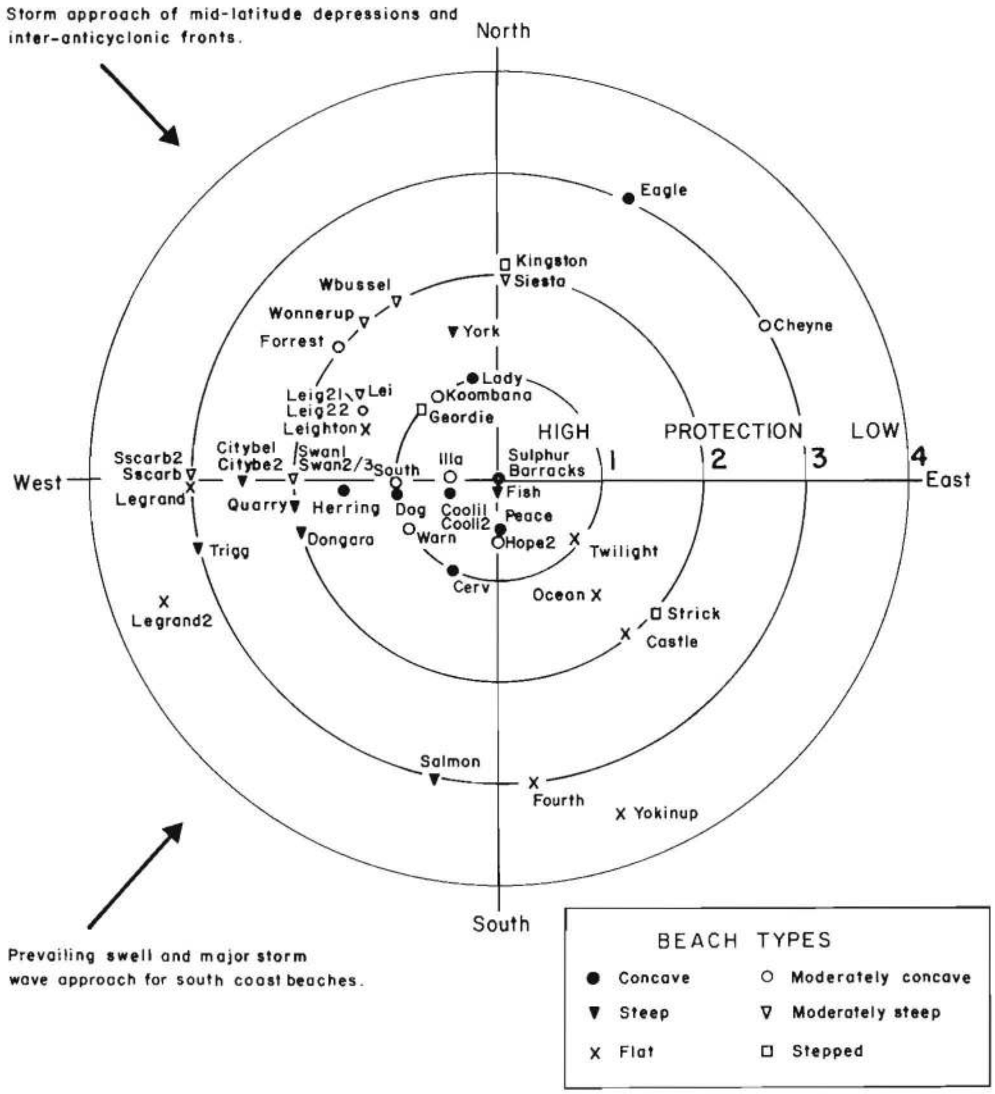


Figure 4. Beach shelter attributed to aspect and degree of protection in Southwestern Australia. Protected beaches are located towards the centre of the shelter plot. Aspect is indicated by compass bearing. Symbols denote the morphotype of each beach.

defined by the cluster analysis (Figure 6). The technique was employed as an exploratory tool to provide a visual representation of the interrelationships between the six morphotypes. An important feature of the result is that the flat and steep beach groups are distinctly separate from the other four groups. It is noteable that the profile dimensions of the flat and steep beaches, is significantly larger than the others. These two groups, Groups 2 and 3, respectively correspond in form with dissipative and reflective morphotypes identified from high energy environments by WRIGHT and SHORT (1984). The four remaining groups are all low energy forms.

Linear discriminant analysis was employed to complete classification of the twelve surveys which were omitted from the cluster analysis due to missing geometric variables. The objective of this analysis was to allocate the surveys with unknown beach form to the 'most appropriate' of the 6 groups. Overall, the majority of the surveys were assigned as steep (group 2) beaches. Ten were identified as concave (group 1) beaches; and nine surveys each were identified as flat (group 3), moderately concave (group 4) and moderately steep (group 5) beaches. Only three stepped beaches were identified. This is presumably a result of sample bias rather than an accurate representation of the frequency with which the particular morphotype occurs in Southwestern Australia.

Sediments and Beach Form

Sedimentologic consistencies within, and associations between, the six morphotypes were examined by canonical variate analysis. This analysis was conducted by using all seven morphologic variables. Due to missing variables, it was necessary to omit four surveys from this analysis. The location

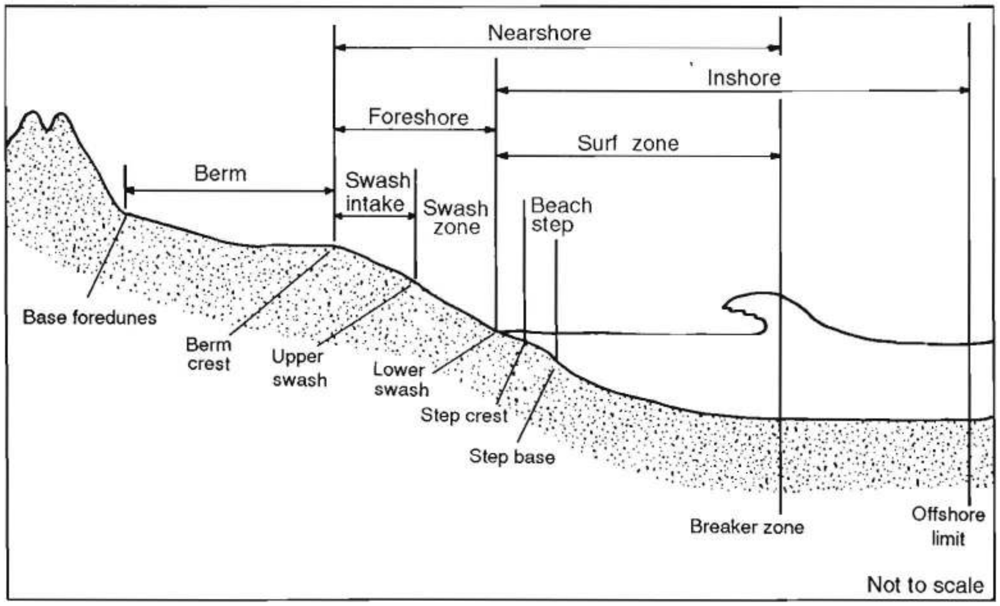


Figure 5. Boundaries of beach profile segments employed in the current investigation.

of surveys within the space of the first two canonical variates provided an indication of the discrimination between the six morphotypes on the basis of their sedimentologic characteristics (Figure 7).

It was apparent, from correlation with the original variables, that the first canonical variate was essentially a measure of grain mass and the second canonical variate was a measure of grain sorting. The results indicate a sequence of fining sedimentary characteristics from coarse sediment on steep beaches, through stepped, moderately steep, concave and moderately concave beach morphologies, to fine sediments on flat beaches.

Extemporary Dynamics and Beach Form

The association between the nearshore dynamics of the morphologic groups was also examined using canonical variate analysis techniques. Variables describing the extempo-

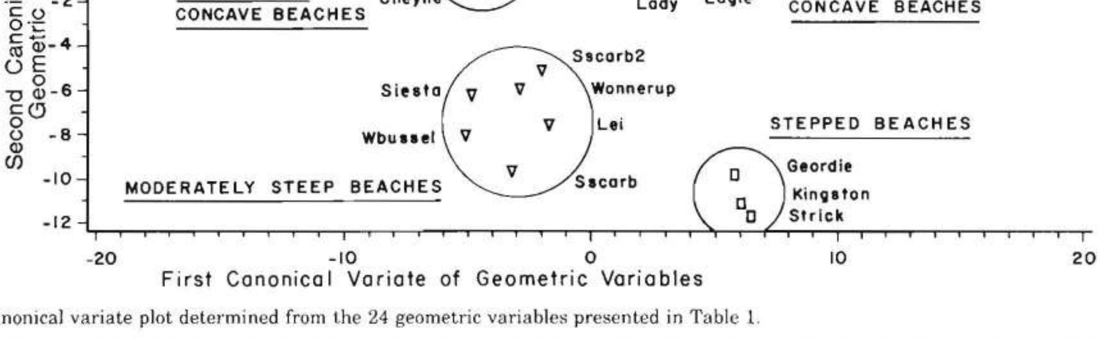


Figure 6. Canonical variate plot determined from the 24 geometric variables presented in Table 1.

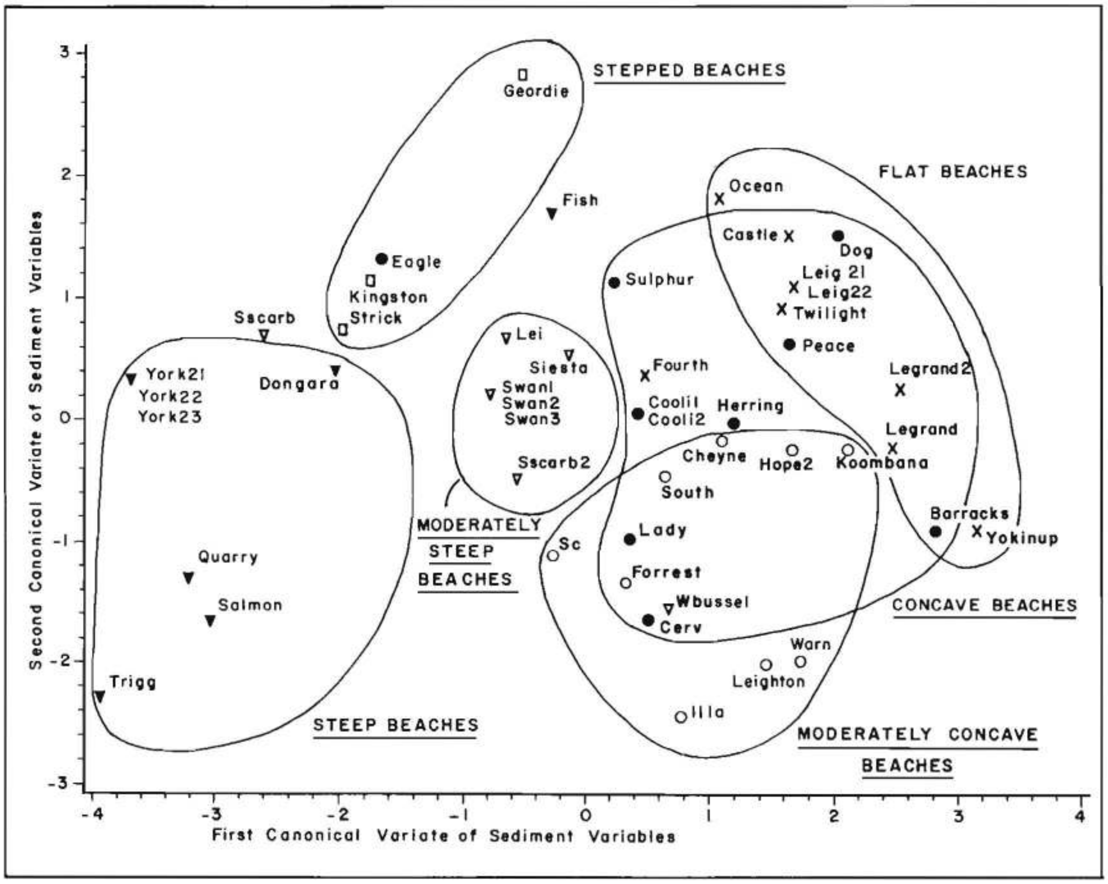


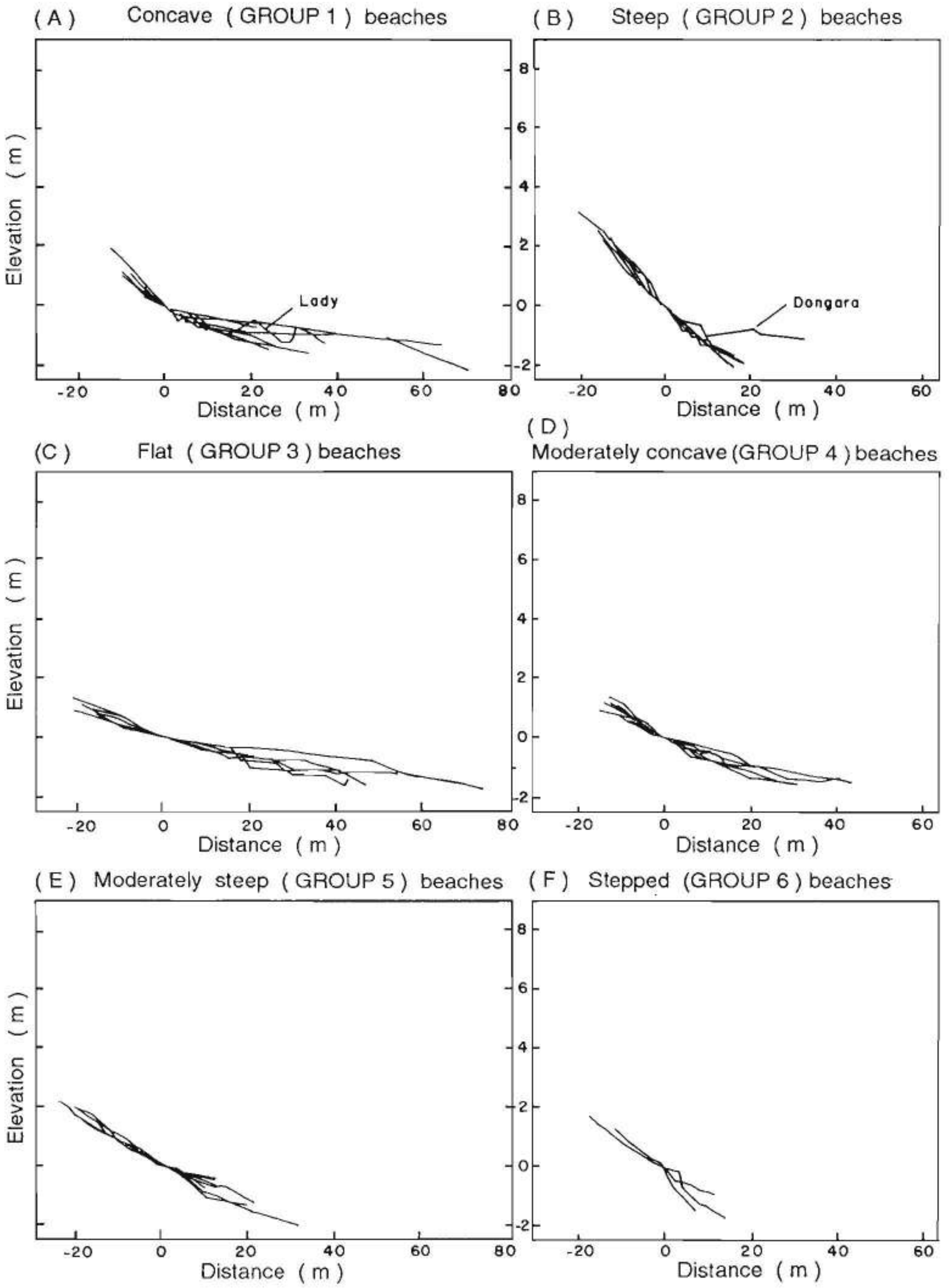
Figure 7. Canonical variate plot determined from the 7 sedimentologic variables presented in Table 2.

rary nearshore dynamics were divided into five components; nearshore wave height, cross-shore currents, longshore currents, swash run-up and swash interactions. Canonical variate analysis was conducted separately on the variables within each of these components to determine whether coupling between the morphology and dynamics could be identified. The greatest distinctions between the six morphotypes were those based on nearshore wave height and longshore currents. The wave records provide a separation of the morphotypes, distinguishing flat and steep beaches, the two morphotypes consistent with high-energy beach classifications, from the lower energy forms. In this case, the first canonical variate essentially describes wave energy.

The association of swash interactions with the morphologic groups was examined because the low-energy beaches are apparently dominated by swash action. The number of swash events and the mode of the swash interactions were determined manually from the video record for 32 surveys following a classification described by HEGGE and ELIOT (1991) as over-taking, over-riding, suppressed and free swash events. The first canonical variate was strongly correlated with the number of swash events ($r = 0.67$), and the number of free swashes ($r = 0.57$). The association is important because it is consistent with the wave height observations and again indicates separation of flat and steep beaches from the lower energy forms.

DISCUSSION AND CONCLUSIONS

Results provided here indicate the existence of a range of low-energy beach types in Southwestern Australia that can be distinguished on the basis of their morphology and sediments. Twenty four variables were available to describe the nearshore profile, from berm crest to offshore zone. These variables describe the geometry of the active part of the beach profile on each of the 52 beaches surveyed. The profiles were considered to represent each beach surveyed because the beaches were essentially planar, with little alongshore variation in their geometry. The 52 surveys were divided into six characteristic morphotypes and the efficacy of the groups determined via visual examination of the survey profiles and canonical variate plots. It was clear from these validation techniques that a suite of six discrete nearshore forms had been identified by the cluster analysis, and that they were distinguished by their dimensions, slope and curvature (Figure 8). The different beach forms were generally associated with different sediments. Despite this, several beaches had sediment characteristics that were different from other


(A) Concave (GROUP 1) beaches

(B) Steep (GROUP 2) beaches

(C) Flat (GROUP 3) beaches

(D) Moderately concave (GROUP 4) beaches

(E) Moderately steep (GROUP 5) beaches

(F) Stepped (GROUP 6) beaches

Figure 8. Surveyed profiles of the six morphotypes, from the berm crest to the offshore limit: (a) concave, (b) steep, (c) flat, (d) moderately concave, (e) moderately steep and (f) stepped.

beaches within the same category. These are apparent as outliers on the canonical variate plot (Figure 7). Physical processes occurring on the beaches were similar under the low energy conditions prevailing at the time of survey. Hence, the morphotypes were not readily distinguishable on the basis of their extemporary dynamics.

Beach Morphotypes

Concave Beaches

The concave (group 1) beaches were characterised by a steep foreshore and swash zone, and a relatively flat inshore zone. This resulted in a markedly concave nearshore profile, with a uniform decrease in curvature with distance offshore. Beaches in this group are small and their beachfaces narrow, generally less than 10.0 m with swash widths less than 5.0 m. The concave beaches also had particularly narrow foreshore and nearshore zones. A moderately sized step (height less than 0.5 m) may also be present on these beaches. Overall, the beaches displayed a wide range of sediment characteristics, and grain sizes ranged from poorly to very well sorted. The mean grain size of sediments on the concave beaches was 0.26 mm and a permeability of 0.007 cm^3s^{-1}.

Steep Beaches

The characteristic feature of the steep (group 2) beaches was a steep and linear beachface slope; also, the inshore zone was often steep. In the surveys conducted, the range of beachface slopes measured was remarkably narrow. Occasionally, minor irregularities were found on the inshore sections of the profile. In this respect the inshore zones at Dongara and Trigg were considerably different from the other beaches in this group. A relatively flat inshore zone at Dongara was associated with a narrow terrace shoal, a shore-parallel bar welded to the beachface. The inshore profile at Trigg is barred, and the beach could be classified as a 'longshore bar-trough' beach following the terminology of WRIGHT and SHORT (1984). The overall dimensions of the steep beaches were generally larger than all but the flat beaches (group 3), with distances from the berm crest to the primary breakers in excess of 40 metres. The mean grain size of the sediments on the steep beaches was 0.56 mm and a permeability of 0.018 cm^3s^{-1}. The beaches displayed moderately well sorted sediments and were the most permeable beaches measured.

Flat Beaches

Flat beaches (group 3) were characterised by broad, flat nearshore zones, as well as by wider foreshore and nearshore zones than any other group. They had the widest swash and surf zones, and the flattest swash and inshore zones. The surf zone at South Le Grand Beach, near Esperance, was 56.0 m and its swash zone was 20.0 m wide under the low energy conditions prevailing. The profiles of the flat beaches were generally uniform, although small irregularities were occasionally observed on the offshore segment of the profile. None of the flat beaches were stepped. Two of them, Ocean Beach and Fourth Beach near Esperance, would appropriately be described as 'longshore bar-trough' beaches, following the terminology of WRIGHT and SHORT (1984). As was anticipated, the flat beaches were comprised of the finest and least permeable sediments. They were also very well sorted. The mean grain size of sediments on the flat beaches was 0.18 mm and a permeability of 0.005 cm^3s^{-1}.

Moderately Concave

The moderately concave beaches (group 4) were similar to the concave (group 1) beaches. However, the nearshore slope and concavity of these beaches was less than that observed on the concave morphotype. The nearshore dimensions of these beaches were generally small, with elevations less than 2.0 m, swash zones narrower than 10.0 m, and surf zone widths less than 15 m. One beach, Hopetoun, had no surf zone at the time of survey. Only one of the beaches surveyed had a small step. Mean grain size of sediments on the moderately concave beaches was 0.26 mm and the sediments were moderately well sorted. Sediment characteristics of the moderately concave beaches were more homogeneous than the sediments obtained from the concave beaches. The sediments of the moderately concave beaches had a mean fall velocity of 0.028 ms^{-1} and a permeability of 0.005 cm^3s^{-1}.

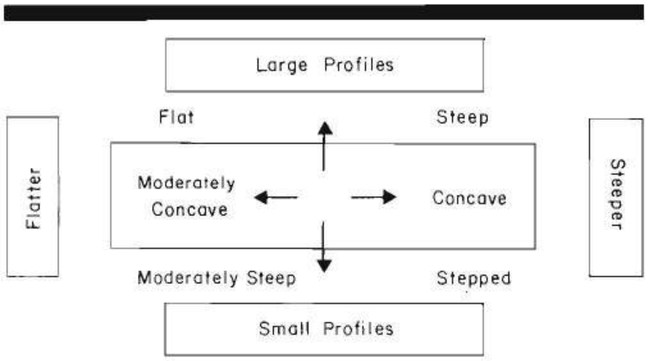


Figure 9. Conceptual model of the associations between beach morphotypes.

Moderately Steep

The nine moderately steep beaches (group 5) identified in this investigation were characterised by steep linear nearshore zones, wide beach face, and considerably high berms. The wide beach face of these beaches was a distinguishing feature and ranged from 15.0 m at Siesta Park Beach to 25.0 m at South Scarborough Beach. Swash zone widths observed were similarly large compared to the other morphotypes, and averaged approximately 10.0 m. The beaches were comprised of moderately well sorted sand with a mean grain size of 0.35 mm, fall velocity 0.04 ms^{-1}, and permeability 0.01 cm^3s^{-1}.

Stepped Beaches

The stepped beaches (group 6) had very narrow nearshore profiles, with relatively steep beachfaces. However, their characteristic feature was the presence of a very large subtidal step beyond the beachface. The widest swash zone observed was at Geordie Bay, with a width of 12.5 m, and the widest surfzone was 6.9 m at Kingston Beach. Mean grain size of the sediments on the steep beaches was 0.36 mm, fall velocity 0.044 ms^{-1}, and permeability 0.014 cm^3s^{-1}. The sediments were well sorted, although not as well sorted as the flat beaches, and they registered the second highest grain size and permeability rates of the beach types sampled.

Overall, the morphologic associations between the six morphotypes may be conceptualised in two dimensions in terms of their dimension and slope (Figure 9). The flat and steep beaches had comparatively large dimensions, but very different slopes; the concave and moderately concave beaches have similar profile dimensions, but may be distinguished by their steepness; and the dimensions of the moderately steep and stepped beaches are similar, but slightly smaller than the concave and moderately concave beaches. The sequence of beach types according to sediment size, from largest to smallest grain size, was steep (group 2), stepped (group 6), moderately steep (group 5), concave (group 1), moderately concave (group 4) and flat (group 3). The beach forms with the most dissimilar sediment characteristics were the steep and flat beaches. These two morphotypes were also dissimilar from the other groups in terms of their dynamics.

Nearshore Dynamics Associated With the Beach Types

Nearshore processes were monitored during each survey to examine whether it was possible to identify dynamic signatures that might be related to the morphologic characteristics of the beaches. The 46 variables describing extemporary nearshore dynamics were grouped in five sets, representing (1) wave regime, (2) cross-shore currents, (3) longshore currents, (4) swash motion and (5) swash interaction. A suite of canonical variate analyses for each of the parameters was conducted to examine differences and associations between the morphotypes.

A visual examination of the canonical variate plots computed for the dynamics indicated that, with the exception of wave regime and longshore currents, only minor differences were apparent between the beach forms. In the analyses, it was possible to separate the flat and steep beach groups from the remaining four morphotypes, on the basis of incident wave regime and swash interaction. The steep and flat beaches are associated with a larger number of free swash events and higher waves respectively. Differences between the remaining four, which are the low-energy beach forms, are more difficult to discern, particularly in so far as their morphologies may partly be inherited from prior high energy events.

Beach sheltering was considered an important factor in the selection of beaches for sampling. The role of sheltering through aspect and protection was established by identifying the beach types on Figure 4. The concave and moderately concave beaches (groups 1 and 4) were associated with the greatest protection. With the exception of Peaceful Bay from the South Coast, the concave beaches are located either on the West Coast and are sheltered by offshore reef chains, or they are located on the east facing, leeward side of Rottnest and Garden Island. The moderately concave beaches are similarly distributed, with exceptions being Cheyne and Hopetoun Beach on the South Coast. Hopetoun is protected by an offshore reef and is similar in its topography to the West Coast beaches.

The moderately steep beaches (group 5) and steep beaches (group 2) are also located on the West Coast. They have westerly aspects and are generally more exposed than the concave beaches. Two of the steep beaches, Fishery Beach near Bremer Bay and Salmon Beach near Esperance, are located on the South Coast. The flat beaches (group 3) generally have a southeasterly aspect and are located on the South Coast. The level of beach protection on these beaches tends to be low, although this is not always the case. Several of the beaches have moderate levels of protection, particularly those in West Coast locations. The stepped beaches appear to be found in locations where there is a moderate level of protection, regardless of aspect. Reasons why this was so were not readily apparent. It is suggested that the sediment characteristics and groundwater conditions play an important role in the development of stepped beaches.

Another means of comparing morphotypes has been suggested by the work of DAVIS and HAYES (1984), DAVIS (1991) and MASSELINK and SHORT (1993) who pointed out that the relative, rather than absolute, amplitudes of waves and tides determines the nearshore morphology. However, this omits the important role played by episodic storm events and other non-tidal fluctuations in water level. The relative importance of these 'surge' events, which can be collectively estimated as tidal residuals, increases as the absolute tide range and modal wave height decrease. Such events are likely to be of particular importance in environments where the range of non-tidal fluctuation in sea-level exceeds the mean annual gravity wave and spring tidal amplitude. This proposition was tested with data extracted from SHORT and WRIGHT (1981), WRIGHT and SHORT (1983) and MASSELINK and SHORT (1993), as well as that collected in the surveys of Southwestern Australia. The mean height of the predicted tides and the tidal residuals at Standard Ports were determined from records provided by the National Tidal Facility. Beach form was then related to the relative contribution of spring tidal range, and the significant amplitude of tidal residuals and an estimate of the mean annual wave height for beaches reported in the literature, the Standard Ports, and the four low-energy morphotypes described above (Figure 10).

Despite the fact that data used provide only broad estimates, and are not specific to the locale investigated, the results indicate a clear distinction between different environments. The very low-energy beaches from Rottnest, Garden Island (Kingston Beach, Herring Bay and Sulphur Bay) and Illawong on the West Coast are subject to very low wave conditions and a relative balance between the amplitudes of tides and non-tidal fluctuation in sea-level. Other low-energy beaches, such as South Scarborough, experience a balance between the three components of sea-level variation. Comparisons for the Standard Ports, for which the data are more reliable, are consistent with this classification and lend confidence to the conclusions. It is interesting to note that the coast of New South Wales, between Sydney and Newcastle, experiences a balanced wave and tide regime, with little contribution from other fluctuations in sea level. The tide-dominated beaches described by MASSELINK and SHORT (1993) plot as anticipated. The strength of these results indicates that a more consistent means of determining characteristic measures for the amplitudes of the oceanographic processes needs to be determined. It also requires that care should be exercised in assigning beaches to wave or tide dominated categories when other sea level fluctuations may be of equal or greater importance.

An Overview

The four low-energy beach types identified in this investigation include the concave, moderately concave, stepped and

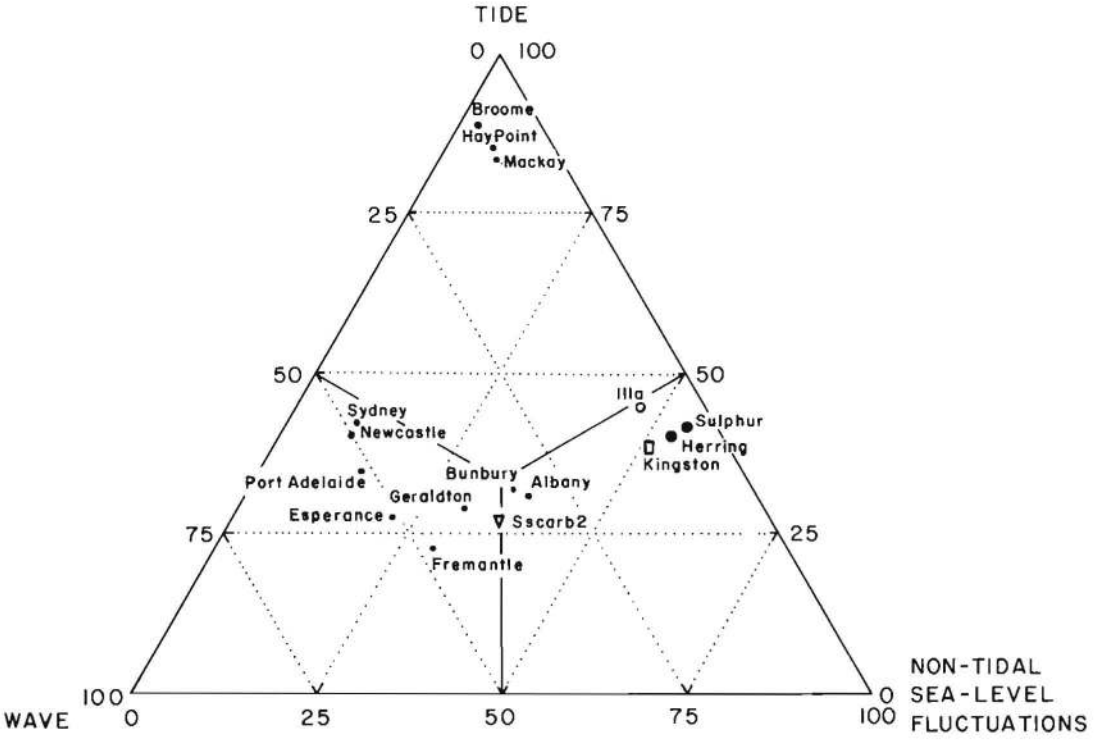


Figure 10. Beach form related to the relative contribution of spring tidal range, and the significant amplitude of tidal residuals and wave height.

moderately steep morphotypes. They are non-barred and display little alongshore variation in their morphology. These beach types are associated with sheltered environments. They are dissimilar to beach types described in wave dominated models, such as that of WRIGHT and SHORT (1984), which generally describe three-dimensional barred beach forms. The low-energy extreme of the wave dominated model of WRIGHT and SHORT (1984) is the 'reflective' beach state. Such beaches are characterised by a steep beachface slope, narrow or non-existent surf zone and no nearshore bar. In this respect they are very similar to the steep beaches (group 2) described here. Although the sheltered beach types from low energy environments do not have bars, they exhibit a wide range of profile slopes and concavities that cannot be adequately described by the single, reflective beach state of WRIGHT and SHORT (1984) or similar low-energy states proposed by other authors. It is also noteworthy that the four low-energy beach types from Southwestern Australia had a much smaller dimension than the two wave dominated beach types described in this paper and reported from elsewhere.

The lack of a strong association of low-energy beach type with the extemporaneous dynamics indicates the overall profile shape is not markedly affected by the modal low energy processes that prevail on sheltered beaches. Elements of the beach morphology and sediments surveyed were related to short-term variation in wave energy, such as those caused by hallmark storm events and sea breeze effects (PATTIARATCHI *et al.*, 1993). In this respect, further research into the short-term, seasonal and interannual variability of the low-energy forms identified in this investigation is likely to provide clarification of the role of inheritance in determining profile configuration, and links with the work reported by NORDSTROM (1992). In Southwestern Australia this research should focus on assessment of the impact and recovery of low-energy beaches to storm events and the very strong sea breeze cycles.

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