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WAVE, BEACH AND DUNE INTERACTIONS IN SOUTHEASTERN AUSTRALIA

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ABSTRACT

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A morphodynamic classification of surfzones, beaches and dunes of the microtidal, low- to high-energy southeast Australian coast is presented.

The first section (A: Waves and beaches) briefly deals with the transformation of deep-water wave energy as it crosses the shelf, nearshore and surfzone. Depending on the deep-water wave characteristics and shelf and inshore morphology, resultant breaker wave energy may be high, moderate or low, and the accompanying beach surfzone morphodynamic state in fine to medium sand beaches either dissipative, intermediate or reflective. Dissipative beaches have wide surfzones with shore parallel bar(s) and channel(s) and predominantly shore-normal circulation; intermediate beaches are characterised by rip circulation, crescentic-transverse bars and megacusps; and reflective beaches by a barless surfzone and steep, cusped or bermed beach. Each beach form has a characteristic level of beach stability, zone of sediment storage and mode of beach and dune erosion.

Landward aeolian sediment transport of swash-deposited sand (Section B) is dependent on the subaerial beach topography and the aerodynamic flow regime across that topography. Characteristic profile shapes are ascribed to each beach type (dissipative, intermediate and reflective). Aeolian sand transport rates are potentially highest on dissipative beaches, moderate on intermediate beaches and lowest on reflective beaches. These rates determine the potential size of foredunes which are correspondingly largest on dissipative beaches and smallest on reflective beaches. The combination of mode and frequency of beach/dune erosion, rates of aeolian sand transport, and foredune volume and morphology provide an explanation of the nature and morphology of landward-occurring, large-scale dune systems. Dissipative beaches are frequently characterised by large-scale transgressive dune sheets; intermediate, by a trend from large-scale parabolic dune systems (high-wave energy) to small-scale blowouts (low-wave energy); and reflective beaches by minimal dune development.

INTRODUCTION

The coastal zone comprises the boundary of the ocean, land and atmosphere. It is a zone of dissipation of marine energy and modification of

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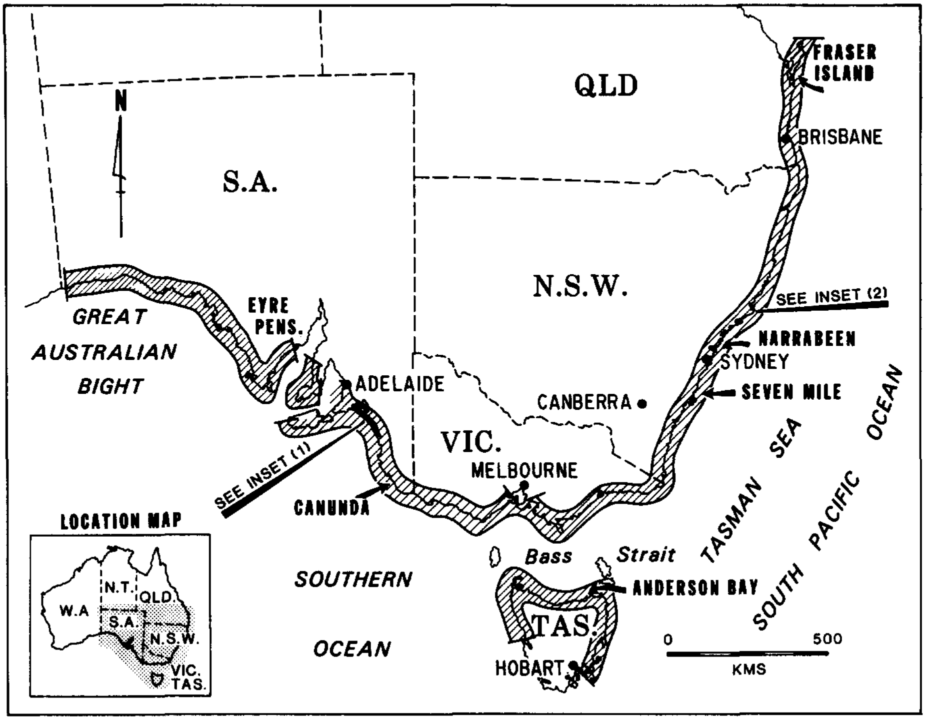
atmospheric processes. The responsiveness of the land boundary to these processes depends on the nature and level of the energy inputs and the nature of the terrigenous boundary. The most responsive domain occurs on wave-dominated sand coasts. This paper is concerned with the response of sand coasts in southeastern Australia to ocean-atmospheric energy inputs. Three zones of interaction will be examined: (1) the transformation of wave energy across the shelf, nearshore and surfzone; (2) the response of sand coasts to this transformation, particularly mesoscale beach and surfzone forms; and (3) the role of onshore winds in transporting wave-deposited sand landward of the swash zone. Wave—beach—dune interactions will be considered only for microtidal, fine-medium sand size beaches at three levels of wave energy and beach response — high wave energy dissipative beaches; moderate energy intermediate beaches; and low-energy reflective beaches (see Short, 1981, for explanation of beach types).

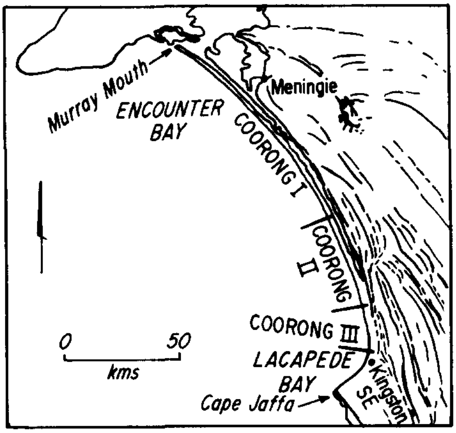
Coastal morphodynamic investigations are usually site specific or time dependent. Each investigation provides a link in the network of interactions that make up the coastal zone. Attempts at comprehending the entire coastal zone date back a century to Suess (1888), (see King, 1972, for a full review). However, not until Davies' work (1964, 1980) did an approach utilising the global wave environments provide a rational basis for future morphogenetic-based classifications. In recent years, the introduction of sophisticated electronic sensors and computer-based technology has lead to a more thorough understanding of this dynamic zone and publication of the first tentative models of wave—beach interactions, see Wright (1982) for review. This increasing awareness of the complexity of the beach-surfzone and its responsiveness to wave conditions required that these interactions be incorporated in future classifications.

In this paper the authors are utilising published and ongoing investigations of shelf, nearshore, surfzone, beach and dune systems along 5400 km of the east and southern Australian coast (Fig.1) as a basis for classifying wave—beach—dune interactions in this region.

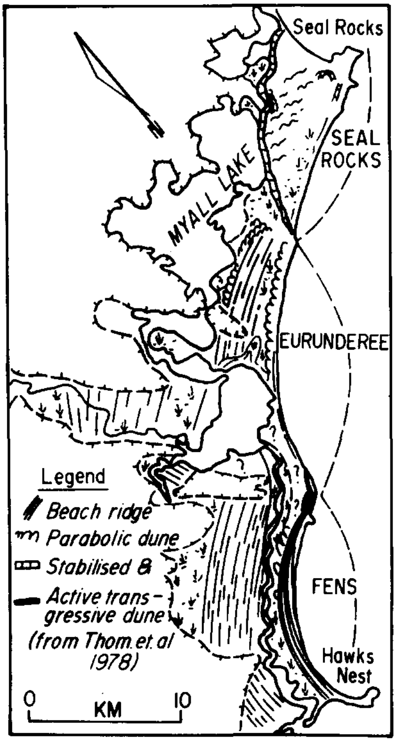
Note that in the following presentation, the southeast Australian coast has particular environmental characteristics which distinguish it from other more well-known environments such as the U.S.A. east and west coasts. These distinguishing characteristics are firstly that wave-induced sediment transport is generally shore-normal, and longshore sediment transport is minimal to absent; secondly that throughout the Holocene transgression large volumes of sediment were supplied to the coast from the continental shelf (Thom et al., 1978, 1981a, b); thirdly that in the last 1000—2000 years much of the shoreline appears to have been stable or slightly regressive; fourthly that this has lead to the large-scale development of foredunes which are readily

Fig.1. The study area of Southeast Australia extending from Fraser Island to the West Australian border, and including Tasmania. The inserts depict two of the main field sites (Coorong and Myall Lakes).





INSET I.



INSET 2.

formed due to the presence of vigorous, native, sand binding perennial plant species (see Davies, 1980, p.160); and fifthly, on prograding beach systems, particularly common in southeast Australia during the early to mid-Holocene, the increased backshore-foredune stability afforded by continual beach progradation resulted in the formation of multiple foredunes (beach ridges) (Thom et al., 1978, 1981a) and minimum to non-existent aeolian instability. Consequently the following dune classification does not apply to such mid-Holocene systems.

Two sites have been examined in detail, the Myall Lakes region in N.S.W. and the Younghusband Peninsula in southeast South Australia (Fig.1). The Myall Lakes region comprises three embayments. The southernmost (Fens) consists of an "inner" (Last Interglacial) beach ridge complex separated from an "outer" (Holocene) beach ridge complex. The middle embayment (Eurunderee) has an inner barrier beach ridge complex and outer episodic transgressive barrier (Thom et al., 1978) comprising parabolic dunes. The Seal Rocks embayment is dominated by a large Holocene episodic transgressive barrier consisting of precipitation ridges, transverse and parabolic dunes (Thom et al., 1981a, b).

The Younghusband Peninsula is a 190 km long Holocene sand barrier forming the most seaward subaerial barrier of a large Quaternary sequence (Sprigg, 1952, 1979; Cook et al., 1977; Idnurm and Cook, 1980). The Peninsula is a composite barrier comprising a prograded beach ridge complex and transgressive dune sequence (Short and Hesp, 1980; Hesp and Short, 1980).

PART A: WAVES AND BEACHES

Nearshore wave modification

Deep-water ocean wave height is determined by the strength, duration and fetch of wind blowing over the sea surface. However, the height of the waves at the coast is further influenced by wave attenuation and refraction across the continental shelf and nearshore zone. Waves expend more energy the wider and shallower the shelf and nearshore, particularly the slope inside the modal wave base, the 20-m depth contour on the moderate to high energy southeast Australian coast. Short and Hesp (1980) calculated the loss of modal deep-water wave energy within eight coastal provinces of the Southeast district of South Australia (Fig.2). The resultant breaker wave energy was then related to the characteristic beach form. They found that within this high-energy west coast swell environment (modal deep-water wave H = 3 m, T = 12 sec) where slopes were steepest (1:150), more than 75% of the deep-water wave energy reached the shore resulting in high-energy dissipative and/or intermediate beaches (Fig.3A). On moderate slopes (1:300) where between 40 and 75% reached the breaker zone, moderate energy intermediate beaches dominated (Fig.3B), while in the lee of shallow slopes (1:800), low-energy reflective beaches received between

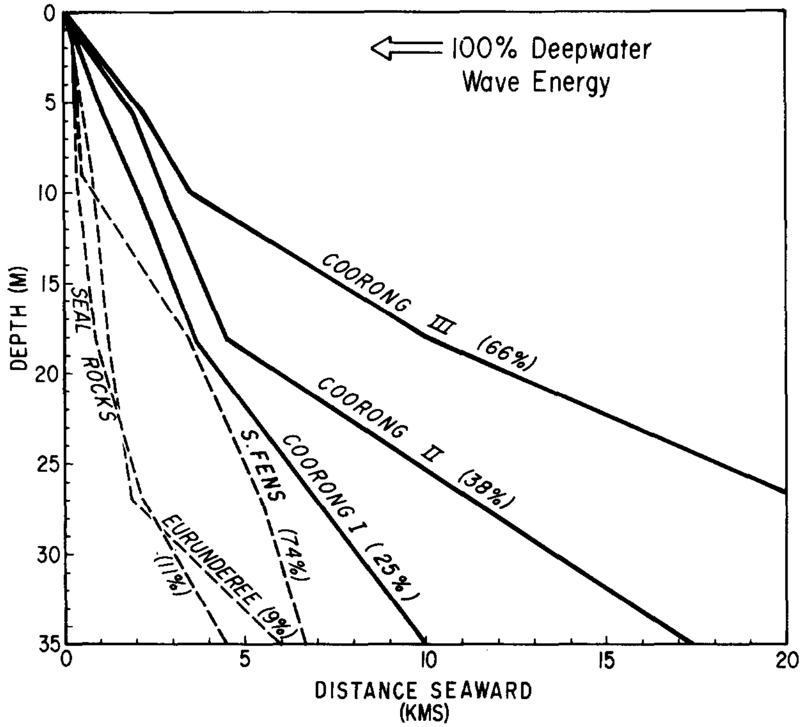


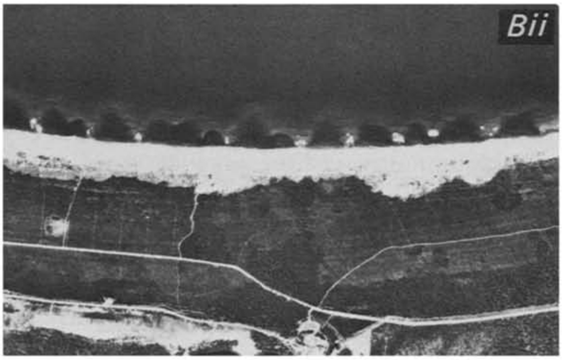
Fig.2. Nearshore and inner shelf gradients at selected locations within the Coorong and Myall Lakes study areas. The percent loss of deep-water wave power by wave attenuation and refraction in reaching the breakpoint is shown in brackets. Note the increasing loss of wave power with decreasing gradient.

25—40% of the deep-water wave energy (Fig.3C). Similarly at Myall Lakes on the moderate to high-energy east coast swell New South Wales coast (modal deep-water wave H = 1.5 m, T = 10 sec) (Fig.1), variation in offshore gradients and resultant wave attenuation produced a similar alongshore gradation in breaker wave energy (Fig.2).

In addition to wave attenuation, wave refraction and diffraction redistribute wave energy at the shoreline. The greater the refraction the longer the length of shoreline over which the wave energy is distributed and the lower the breaker wave energy per unit of shoreline. Short (1978, 1979a) relates the varying degrees of wave refraction within a beach system to the relative level of breaker wave energy along the beach. The highest waves are associated with areas of least refraction, and lowest waves with areas of most refraction. Breaker wave energy is therefore a function of the deep-water wave energy, less the amount lost to wave attenuation and redistributed by wave refraction.


A


Bi


Bii


C

Breaker wave energy and beach form

Recent classification of beach systems by Sasaki and Horikawa (1975, 1979) Short (1978, 1979b, 1981) Wright et al. (1979) and Wright (1981) all emphasise the relationship between the morphodynamics of the beach-surfzone and the level of breaker wave energy and/or the nature of the surfzones dynamic response to that energy. In Table I the three wave energy levels and accompanying surfzone dynamics are related to the resultant beach and surfzone morphology. Short (1981) found in southeast Australia that on medium-fine sand beaches modally high waves (>2.5 m) produce

TABLE I

Modes of wave—beach interaction

Wave energy (Breaker height[1] in m)	Surf zone dynamics[2]	Beach-surfzone morphology	Reference — terminology
High (>2.5)	Dissipative $\epsilon < 20$	Low gradient shore parallel bars – channels with predominantly shore normal circulation; and/or mega rip circulation[3]	Sasaki — Infragravity Short — Beach stages 6, 5′ Wright et al. — Beach type 1, 2
Moderate (1—2.5)	Intermediate (rhythmic) $2.5 < \epsilon < 20$	Rips, crescentic bars, megacusps, etc., rip circulation	Sasaki — Instability Short — Beach stages 5,4,4′, 3,3′ Wright et al. — Beach type 3,4,5
Low (<1)	Reflective $\epsilon < 2.5$	Barless steep beach-face cusps, berm, wave reflection	Sasaki — Edge wave Short — Beach stages 2,2′, 1 Wright et al. — Beach type 6

[1] Breaker height levels are based on observations on fine to medium sand beaches in south east Australia, in other locations they should be used as general indicators of wave energy of required, rather than specific levels.

[2] Guza and Inman's (1975) terms, *dissipative* and *reflective* are used to describe the high- and low-energy surf dynamics, while the term *intermediate* is attached to the moderate energy beaches and encompasses Homa-Ma and Sonu's (1962) term, rhythmic. ϵ= Surf scaling parameter, see Guza and Inman (1975).

[3] Mega-rips, and "super" rips, see Short (1979b).

Fig.3. Examples of characteristic beach types around Southeastern Australia. A, the highly dissipative Coorong I region with low-gradient beach and shore parallel bars and channels. Surfzone 500 m wide, breaker height approximately 3—4 m. Bi, high-energy intermediate beach in Eurunderee embayment (Myall Lakes) illustrating large-scale crescentic bar/trough morphologies. Bii, moderate energy intermediate beach in Fens embayment (Myall Lakes) showing well-developed crescentic bars and rip channels. C, low-energy reflective beach at Agnes Water (Qld.) illustrating steep beach face and narrow surfzone dominated by cusp circulation.

dissipative surfzones with shore-parallel bars and channels; moderately high waves (1.0—2.5 m) result in intermediate surfzones with characteristic rhythmic longshore topography — rips, crescentic bars, megacusps, etc.; and low waves (< 1 m) generate reflective beaches composed of steep cusped or bermed beach faces and narrow barless surfzones. In view of the published details of the above levels of wave—beach interaction, and for simplicity, the three levels of wave energy and beach type (high energy—dissipative, moderate energy—intermediate, and low energy—reflective) will be used as a basis for classification in the remainder of this paper.

Beach mobility, beach form, and zones of sediment storage

Associated with each beach type are characteristic levels of beach and backshore mobility, beach form and zones of sediment storage (Short, 1981). The mobility of a beach (i.e. movement normal to the shoreline) can be measured in terms of the beach mobility which is defined as the standard deviation of the mean position of the shoreline (Dolan et al., 1978), and backshore mobility here defined as the coefficient of variation of mean shoreline position. Low values indicate low mobility, high values a mobile beach or backshore and therefore higher susceptibility to erosion—accretion episodes. The beach form is simply the characteristic morphology of a beach as it resides in its particular range of mobility. Highly mobile beaches will have a wider range of forms than beaches with low mobility. Likewise the zones of sediment storage will reflect the beach mobility and form as it is ultimately the exchange of sediment between the nearshore, surfzone and beach that determines the form and mobility. The following summary of beach form and associated mobility is based on the aforementioned published results (Table I) and long-term surveying of beach profiles around southeast Australia on beaches composed of medium to fine grain size material, in microtidal environments.

Dissipative beaches

Dissipative beaches are a response to modally high wave conditions coupled with an abundant supply of medium to fine sand. Potential onshore wave-induced sand transport is at a maximum on dissipative beaches. Their morphology is characterised by a wide low-gradient beach face and subdued shore-parallel bar(s) and channel(s) (see Goolwa and North Seven Mile, Figs.3a and 4a). Wave energy arriving at incident frequency at the outer breakpoint decays while energy at infragravity frequencies grows in the inner surfzone. This produces infragravity standing oscillations in the swash zone which take the form of 1 m plus high bores (Short, 1979b; Wright, 1982; Wright et al., 1982). Dissipative beaches possess wide, low-gradient subaerial beaches with a low to moderately stable shoreline (i.e. low mobility, Short, 1981), Table II. They experience a low temporal frequency of erosion, but one which is spatially continuous alongshore causing parallel backbeach-foredune scarping (Short and Hesp, 1980).

TABLE II

Morphometric parameters of selected beach profile locations

Beach type	Dissipative		Intermediate			Reflective
Location	Goolwa	N. Seven	Mid Seven	Narrabeen	Collaroy	Fishermans
n	2	7	7	85	85	18
Months	18	15	15	66	66	18
Hb(m)	3	1.5	1.5	1—1.5	0.5—1	<0.5
Gd(mm)	0.2	0.25	0.25	0.3	0.3	0.3
Gradient	1:33	1:39	1:37	1:15	1:12	1:9
B-S	6	5—6	5	3—4	2—3	1
$\bar{y}b$ (m)	90	105	110	42	36	27
$\sigma\bar{y}b$ (m)	10	7	9	14	9	5
CV	0.10	0.07	0.08	0.33	0.25	0.18
$\bar{V}$ (m^3)	120	135	170	180	65	40
$\sigma\bar{V}$ (m^3)	low	30	55	90	45	12
$\bar{V}/\bar{y}b$	1.3	1.3	1.5	4.3	1.8	1.5

n: sample size; months: length of survey; Hb: modal wave height; Gd: mean grain size; Gradient: subaerial beach slope; B-S: modal beach stage; $\bar{y}b$: mean beach width; $\sigma\bar{y}b$: standard deviation of $\bar{y}b$; CV: coefficient of variation of $\bar{y}b$; $\bar{V}$: mean subaerial beach volume and standard deviation $\sigma\bar{v}$.

Intermediate beaches

Intermediate beaches occupy states between the fully dissipative and fully reflective. Beach mobility ranges from moderate to high (mid Seven Mile and Narrabeen, Fig.4 and Table II) to moderate-low (Collaroy, Fig.4 and Table II) with the trend from dissipativeness and high wave energy to reflectiveness and low wave energy. In addition, rip circulation provides an important spatial control on beach form and ultimately beach erosion. With beach erosion being greatest in rip embayments (Short, 1979b; Wright, 1981).

Because intermediate beaches are associated with a wide range of wave height and energy, and span morphologies between dissipative and reflective they can be further subdivided into three levels dependent on the modal wave height, beach form and zones of sediment storage (Table III). The highest energy form (beach stage 5, Short, 1979b) stores potentially active sediment in the surfzone as crescentic/transverse bars. The beach face, though often cusped, is usually of low gradient and relatively wide and stable (see mid Seven, Fig.4). The moderate energy beach (beach stage 4) stores sediment equally between the subaerial beach and the surfzone. The continual exchange between the two leads to maximum beach mobility (see Narrabeen, Fig.4). Crescentic bars and megacusps are the dominant morphologies. The beach is of less width and higher gradient. The lower energy (beach stage 3) stores more sediment in the subaerial beach and has less persistent rip circulation leading to lower beach mobility, but relatively higher beach gradients and lower beach width (see Collaroy, Fig.4).

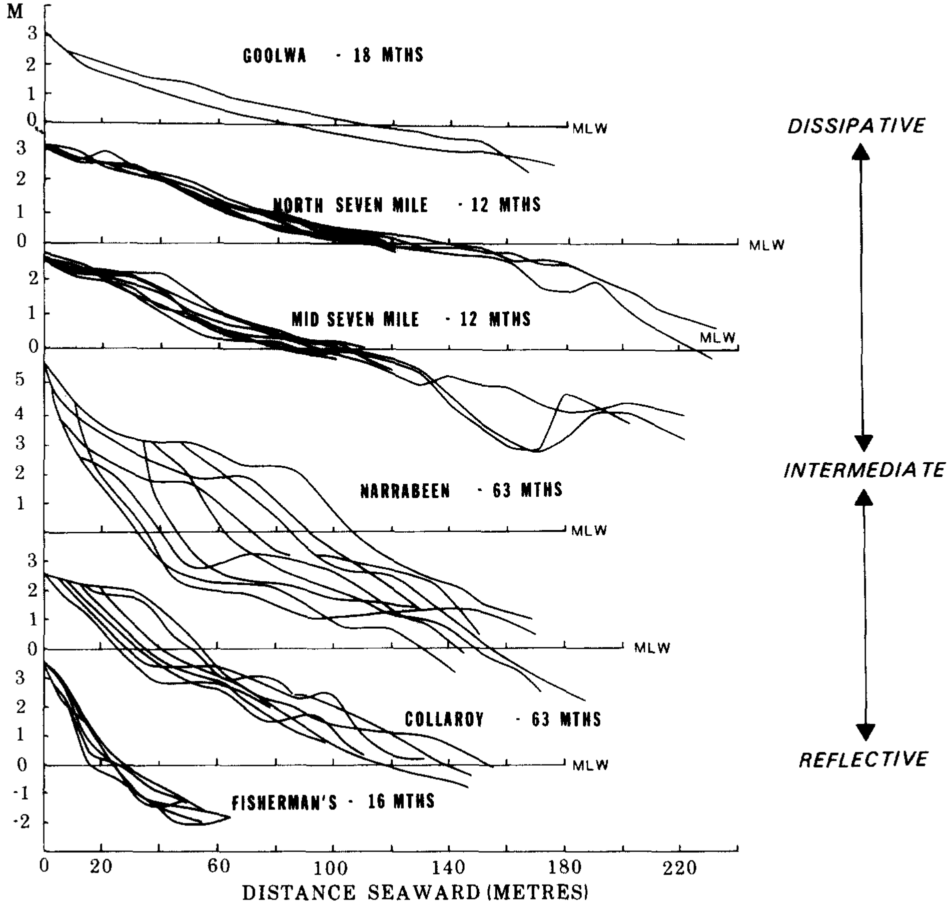


Fig.4. Beach profile envelopes for dissipative through reflective beaches in southeast Australia (see Fig.1 for location). The envelopes represent the size and extent of the beach sweep zone during the period of observation. See Table II for morphometric parameters of the above beaches.

Reflective beaches

Reflective beaches form in response to low modal wave conditions (Short, 1979b; Wright et al., 1979a). Potential onshore wave-induced sand transport is at a minimum. Sediment is stored on the subaerial beach as a steep, reflective beach face berm (see Fishermans, Fig.4 and Table II). Subaerial beach width is narrow. The surfzone is sediment deficient and relatively deep. During modal wave conditions the beach face maintains a dynamic equilibrium having very low beach mobility. *Minor* beach erosion occurs quite frequently but is of limited extent and duration (Short, 1979b; Wright, 1981). Beach recovery is rapid and the foredune, though scarped occasionally, tends to remain relatively stable over time.

TABLE III

Wave, beach and dune interactions in southeastern Australia

A) MODAL WAVE HEIGHT	B) MODAL MORPHO-DYNAMIC STATE	C) MODAL BEACH STAGE (WAVE HEIGHT)	D) BEACH MOBILITY INDEX	E) MODE OF BEACH EROSION	F) NATURE OF BACK BEACH EROSION		G) NATURE OF BACK BEACH ACCRETION		H)POTENTIAL FREQUENCY (> 100YRS) OF TOTAL FOREDUNE DESTRUCTION	I) GIVEN E,F,G AND H - NATURE OF LANDWARD DUNES
					TEMPORAL	SPATIAL	POTENTIAL AEOLIAN SEDI-MENT TRANSPORT	FOREDUNE SIZE		
HIGH (>2.5m)	DISSIPATIVE	6,5' PARALLEL BAR/S CHANNEL/S SURF ZONE. WIDE,LOW GRADIENT BEACH.	LOW	LOW FREQUENCY WAVE SET-UP (SWASH BORES)	LOW (1:10yrs) DUNES : ALONGSHORE SCARPING OVERWASH:AT TOPOGRAPHIC LOWS	LATERALLY CONTINUOUS	HIGH	LARGE (15 - 30 HIGH) (>100m WIDTH)	MODERATE	LARGE SCALE TRANSGRESSIVE DUNE SHEETS
MODERATE (1 2.5 m)	INTERMEDIATE	5 (2 2.5m) CRESCENTIC BARS, LOW-MODERATE GRADIENT BEACH.	LOW-MODERATE	RIP EMBAYMENT EROSION	MODERATE DUNES:SCARPING IN RIP EMBAYMENTS. (SPACING 1 km). OVERWASH:IN LEE OF RIP EMBAYMENTS.	DISCRETE	HIGH-MODERATE	HIGH-MODERATE	MODERATE-HIGH	LARGE SCALE PARABOLICS TO DUNE SHEETS.
		4 (1.5 - 2m) CRESCENTIC BARS -MEGACUSPS. VARIABLE LOW-MODERATE GRADIENT BEACH.	HIGH		MODERATE (1:3-5 yrs) DUNES:SCARPING IN RIP EMBAYMENTS. (500m - 1km). OVERWASH:IN LEE OF RIP EMBAYMENT.	DISCRETE	MODERATE	MODERATE (10 - 20 m HIGH) (< 100 m WIDTH)	HIGH	LARGE SCALE PARABOLICS LARGE BLOWOUTS.
		3 (1 - 1.5 m) RIP CELLS MODERATE-HIGH GRADIENT BEACH.	MODERATE-LOW		MODERATE DUNES:SCARPING IN RIP EMBAYMENTS (< 500 m) OVERWASH:IN LEE OF RIP EMBAYMENTS.	DISCRETE	MODERATE-LOW	MODERATE SMALL	MODERATE LOW	DISCRETE BLOWOUTS
LOW (< 1m)	REFLECTIVE	2, 1 BARLESS NARROW SURFZONE, HIGH GRADIENT BEACH.	LOW	HIGH FREQUENCY WAVE RUN-UP	HIGH (1: 1-2 yrs) DUNES:CONTINUOUS SCARPING. OVERWASH:AT 'LOWS'.	CONTINUOUS	LOW	SMALL (< 10 m HEIGHT) (< 50 m WIDTH)	LOW	FOREDUNE SCARPING, OCCASSIONAL SMALL SCALE BLOWOUTS.

The aforementioned beach types possess characteristic morphologies, dynamics, modes of erosion—accretion, zones of sediment storage and levels of beach and backshore mobility (Tables II and III). To link these interactions to coastal dunes the impact of onshore winds and aeolian sand transport within each beach type is now considered.

PART B: BEACHES AND DUNES

Landward aeolian sand transport is a function of the volume of beach sand available for transport, the shape and width of the subaerial beach, and the nature of the aerodynamic flow across the beach. Assuming the presence of vegetation to trap aeolian sand on the backshore, variations of these factors determine the gross morphology of foredunes.

Subaerial beach profiles

The gradient and width of the subaerial beach have a pronounced effect on the potential rate of landward aeolian sediment transport. In general, when there is a flow across a surface, the flatter the surface, the less the velocities fluctuate or are reduced and the greater potential for continuous sand transport across that surface (see e.g. Bowen and Lindley, 1977; Hsu, 1977). Abrupt topographic changes induce changes in the velocity fields resulting in flow separation, and internal boundary layer development. These act to reduce the velocity gradients, surface shear stresses and the volume of sand transported. Consequently, the characteristic subaerial morphology or topography of a beach has a direct effect on the volume and rate of landward sand transport (Hesp, 1982).

The subaerial morphology of fully dissipative beaches is characterised by a wide, flat, or gently sloping backshore and beach face (Fig.4). Minimum disturbance of the wind flow occurs across these beaches and potential sand transport by onshore winds is at a maximum. Figure 5A illustrates lines of equal velocity derived from wind profiles (Hesp, 1982) measured over a dissipative subaerial beach. The lines are expressed as a percentage of a 4-m wind speed at 4-m elevation (100%). Flow disturbance is minimal and mean velocities and shear stress display a slight landwards increase towards the bed up the gentle slope. Potential sand transport by onshore winds is at a maximum across the whole beach during low tide.

The subaerial morphology of intermediate beaches varies through a number of morphologic states, depending on the modal beach state and the form and volume of sand stored on the beach. Consequently, the beach face is relatively steep on moderately reflective and low on moderately dissipative beaches. In addition, alongshore morphologic variations may be pronounced (more reflective off megacusp bays, more dissipative off megacusp horn/bar attachments). The backshore may be relatively flat, although more often a runnel, or "berms" and runnels are present. With increasing wave dissipation, subaerial gradients increase in width and decrease in slope,

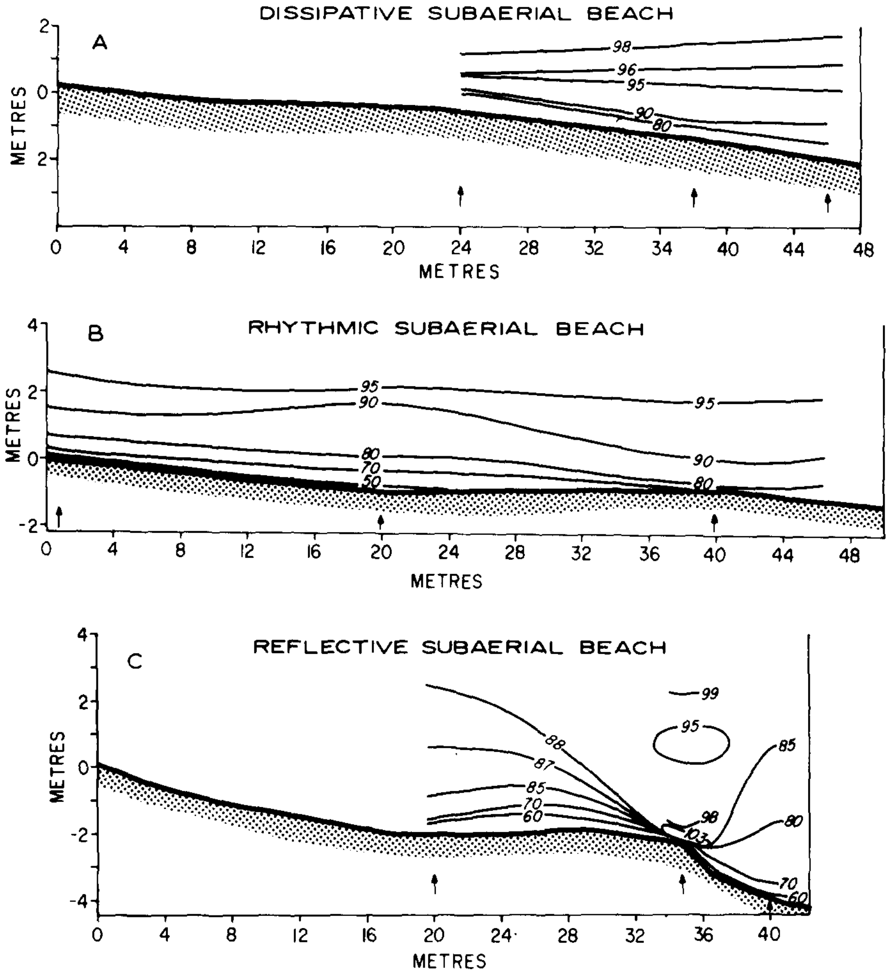


Fig.5. Lines of equal mean velocity expressed as a percentage of a 4-m wind velocity (100%) measured over dissipative (A), intermediate (B), and reflective (C) subaerial beaches. The arrows indicate velocity profiling locations.

causing wind profile disturbance to range from moderate to low, and potential aeolian sand transport to vary accordingly from moderate to relatively high. Figure 5B illustrates lines of equal mean velocity derived from wind profiles measured across a low-energy intermediate beach profile (beach stage 3). Even though the berm is low, and the runnel subtle, marked reduction in wind velocity and shear stress, and hence potential sand transport occurs across a significant portion of the back beach.

The subaerial morphology of reflective beaches is characterised by a steep berm/cusp face, berm crest, and flat or gently landward sloping back berm. The back berm and upper beach is usually narrow. Figure 5C illustrates a typical steep reflective beach profile. Wind velocities increase rapidly up the berm face, and a jet flow exists at the berm crest. The latter is similar to one described for ice pressure ridges by Hsu (1977). Flow separation occurs to the lee of the crest and velocities are markedly reduced over the runnel. Sand transport is minimal on the berm face due to the usual presence of wet sand and/or swash. It may be high on the immediate berm crest if the sand is dry, but is very low across the runnel region. This leaves only a narrow backbeach area available for aeolian sand transport.

Given equal reception of onshore wind energy, landwards aeolian sand transport varies according to the morphology, gradient and width of the beach. Dissipative beaches experience the lowest flow disturbance, intermediate beaches moderate to low flow disturbance depending on the profile shape, and reflective beaches the highest flow disturbance. Potential aeolian sand transport is greatest on dissipative beaches and least on reflective beaches. Foredunes are accordingly potentially largest on modal dissipative beaches, of moderate size on modal intermediate beaches and smallest on modal reflective beaches (Table III).

Foredune morphology and the occurrence and extent of dune transgression

By combining the factors responsible for subaqueous and subaerial beach state with the dominant modes of beach erosion and accretion, it is possible to predict the relative potential for foredune formation, the characteristic foredune morphology, and the nature and extent of dune transgression to the lee of foredunes.

High-energy dissipative beaches potentially have the largest foredunes (Fig.6). During accretionary periods, these may also be the most stable, and in southeast Australia be covered by dense vegetation. However, more usually foredunes in lee of dissipative beaches range through a number of geomorphic states, from highly stable, well-vegetated, topographically laterally continuous forms, to highly unstable, poorly vegetated, hummocky residuals. The unstable end of the range is often initiated by large-scale, laterally continuous wave erosion during extreme storm events. A situation evolves where the high, scarped and/or breached foredunes are open to aeolian destruction and over time a large volume of the foredune may be transported landwards. Beach sand may also be directly incorporated into this landward movement through foredune breaches. This erosion may initiate further aeolian destruction of more landward lying dunes. If such destruction occurs, large-scale, transgressive dune sheets may be formed (Hesp and Short, 1980).

Moderate-energy intermediate beaches represent a transition zone from initially high to low potential aeolian transport, and from large to small foredunes, as they trend from the more dissipative to the more reflective beach states (Fig.6). This range in size and morphology is illustrated for Fens embayment in Fig. 7A, I to III. Foredunes are characterised by lateral morphologic variation, often displaying a cusped form alongshore (more than hundreds of metres), and multiple phases of erosion and accretion.

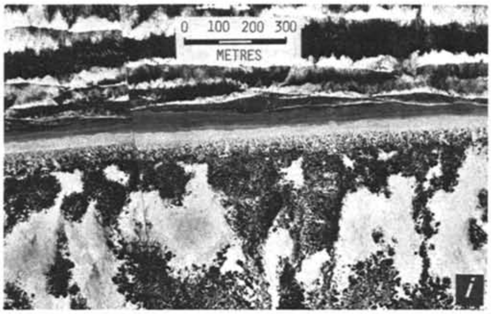
Foredune instability and morphology is related to regular scarping at discrete locations (in lee of rip embayments) which are spatially variable over time. Such localised, arcuate erosion is aggravated by wind erosion and often leads to the formation of blowouts. The frequency of blowout formation appears to be related to the degree of rip embayment erosion as reflected in the mobility index. In southeast Australia, foredune instability appears greatest in the lee of high-energy intermediate beaches (modal beach stage 5, Short, 1979b), and least in the lee of low-energy intermediate beaches (modal beach stage 3). Over time, the occurrence of unstable foredunes encourages the formation of multiple blowouts which may lead to large-scale nested parabolic dunes on high-energy intermediate beaches (e.g. Canunda and Eyre Peninsula, South Australia; Eurunderee embayment, N.S.W.; Anderson Bay, Tasmania, Fig.1), and a gradation to a few discrete parabolic dunes or blowouts on medium-low energy intermediate beaches (e.g. lower Fens, N.S.W., Fig.7A). High-energy intermediate beaches may also display unvegetated, transgressive dune sheets where coalescence of blowouts/parabolics has occurred. These are typically of less volume and size than those of high energy dissipative beaches.

Foredunes of reflective beaches tend to be small (Figs.6b and 7A) and asymmetric with scarped stoss faces, produced by either laterally continuous scarping or localised erosion in the lee of erosion cusps. Following erosion, beach recovery is rapid (2—4 weeks), and this factor coupled with the generally low foredune, and low aeolian sand transport reduces the risk of dune destruction by aeolian means. Reflective beaches therefore are characterised by one to three or four dune ridges, and potential dune transgression is limited to non-existent.

Wave, beach and dune interactions — a classification

The foregoing sections have described processes on microtidal, medium-fine sand size beaches. Three modal surfzone-beach states have been distinguished. These are high wave energy dissipative beaches, moderate wave energy intermediate beaches and low wave energy reflective beaches. Each beach state is characterised by a particular combination of morphology and dynamics. The classification of the full range of interactions is given in Table III. In Figs.8 and 9 we present surfzone, beach and dune data for the Younghusband Peninsula and Myall Lakes region. These figures provide evidence of the relationships between modal surfzone/beach morphology, foredune morphology, and dune volume.

Modally dissipative beaches are characterised by high wave energy, a wide surfzone consisting of parallel bars and troughs, a low gradient, wide beach experiencing low mobility, minimum wind flow disturbance, high potential aeolian sand transport and potentially large foredunes. Over time (thousands of years) the high potential wave-induced sand transport provides the largest volume of sediment for dune formation. Dune fields are thus of greatest volume and extent in the lee of dissipative beaches (Table III and Figs.7, 8 and 9).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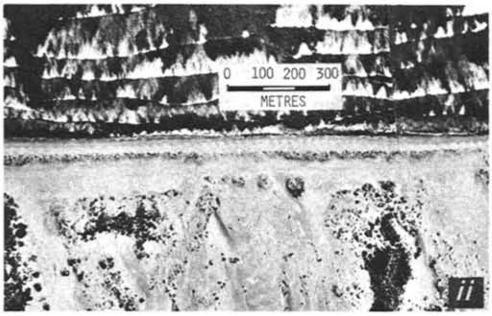
METRES
i

(a)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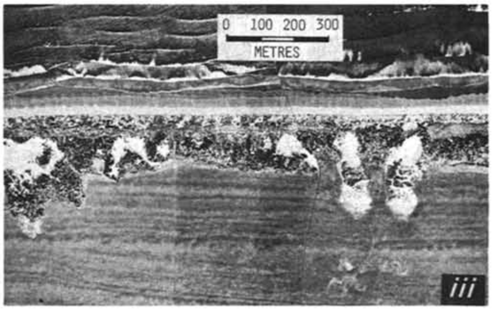
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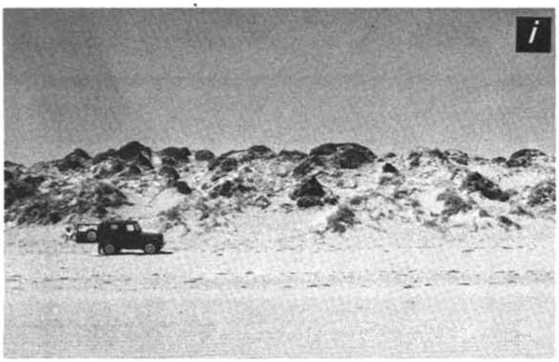

i

(b)

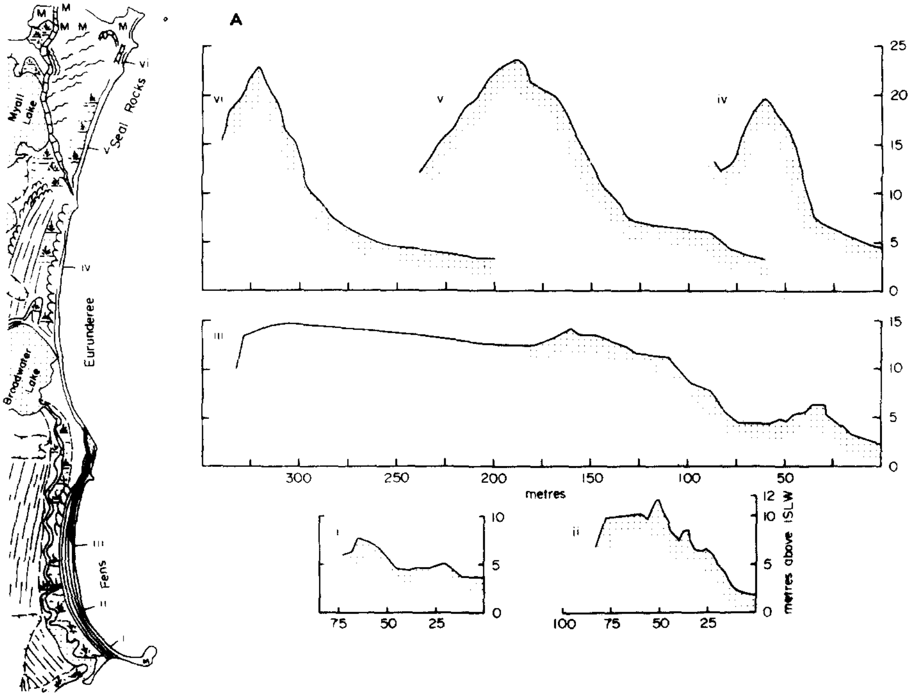
(b)

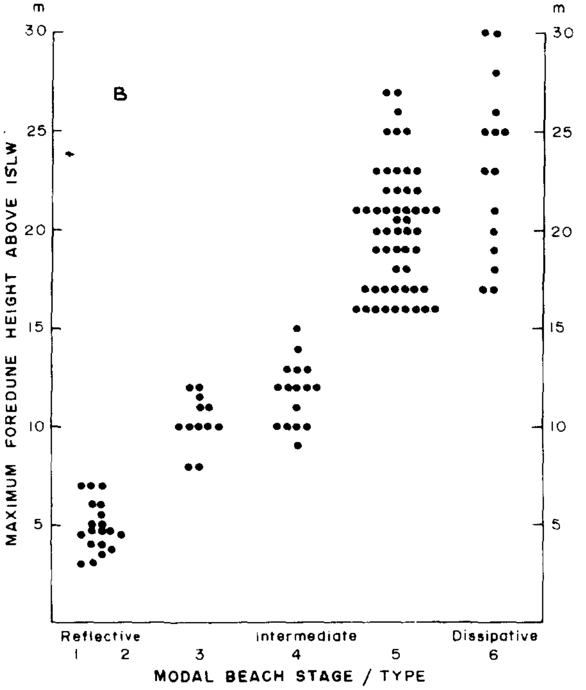
(b)

(b)

Fig.6a. Vertical aerial mosaics of portions of the Coorong region, S.A. i. Large-scale, moderately vegetated, stable foredune in Coorong I (at 75 km). Note blowouts/parabolics to landwards. ii. Highly erosional foredune in Coorong II (at 116 km). Note wide deflation basin and active transgressive dune sheet to landwards. iii. Two foredunes and beach ridge system in Coorong III (154 km). Note outer foredune stability and small blowouts on inner foredune.

Fig.6b. i. Large-scale foredune on a high-energy dissipative beach (Coorong I, 75 km). ii. Large-scale scarped foredune with blowouts and incipient foredune at the base of the scarp on a high-energy intermediate beach (Seal Rocks). iii. Moderate size foredune with small-scale erosional topography on a moderate energy intermediate beach (mid-Fens embayment). Note the cuspate erosion scarp resulting from discrete rip embayment erosion. iv. Low, very stable foredune on a low-energy reflective beach (Agnes Waters, Qld).


A
M
Myall Lake
Seal Rocks
Eurunderee
Broadwater Lake
Fens
vi
v
iv
iii
ii
i
metres
metres above ISLW
300
250
200
150
100
50
0
5
10
15
20
25
75
50
25
100
12


B
m
30
25
20
15
10
5
MAXIMUM FOREDUNE HEIGHT ABOVE ISLW
Reflective
Intermediate
Dissipative
1
2
3
4
5
6
MODAL BEACH STAGE / TYPE

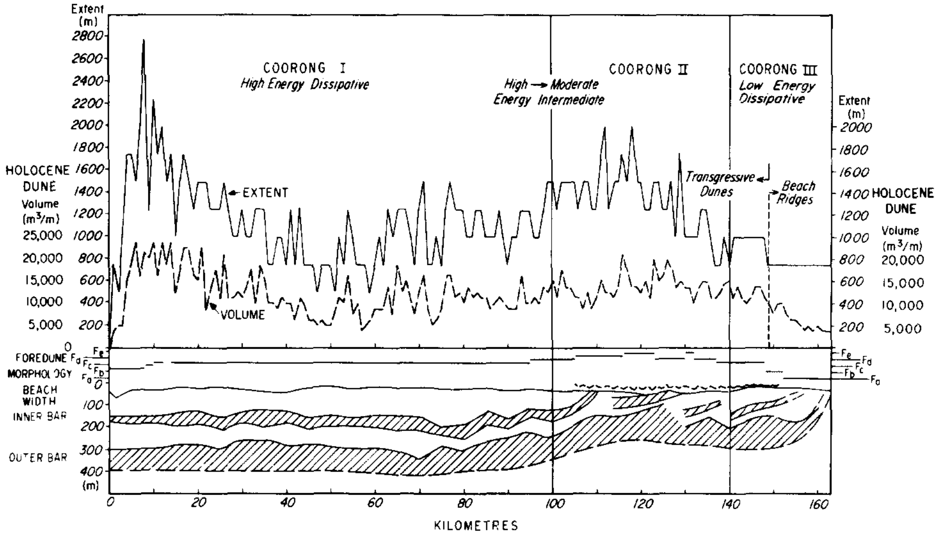


Fig.8. Morphometric parameters for 165 km of the Coorong embayment (see Fig.1 for location), illustrating the longshore variation in surfzone morphology and width, beach width, foredune morphology, extent of dune transgression and dune volume. Bar morphology was plotted from 1975 aerial photographs. Beyond 100 km the variability in the bar morphology and rhythmic lines on the beach indicate intermediate beach and surfzone morphologies. Foredunes are classified according to their morphology, degree of vegetation cover and stability. Morphologic complexity increases and stability decreases from Fa to Fe types (Appendix).

Modally intermediate beaches are characterised by moderate wave energy. Surfzones are complex, consisting of three-dimensional rhythmic topographies including crescentic bars and troughs, and varying scales of rip systems. As intermediate beaches morphology moves from the dissipative to the reflective state, rip spacing and size decreases, surfzone width decreases, and subaerial beach gradient increases as width decreases. Beach mobility trends from moderate to high to moderate with declining wave energy. Wind flow disturbance increases with increasing beach gradient. Potential aeolian sand transport and foredune size decreases as intermediate beaches trend from dissipative to reflective. Over time, a similar trend is found in landward dune fields, as potential wave-induced and wind-induced sand transport decreases with decreasing dissipativeness.

Modal reflective beaches are characterised by low wave energy, minimum surfzone, a high gradient, narrow, low mobility subaerial beach, high wind

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Fig.7A. Topographic surveys of foredunes with Fens embayment (Myall Lakes). See insert for locations. Note the northwards increase in foredune size and morphologic complexity with increasing dissipativeness. B. Relationship between modal beach/stage type (Short, 1979b) and maximum foredune height above ISLW for Myall Lakes beaches. Data derived from ground surveys 100 m apart in the mid-region of selected modal beaches.

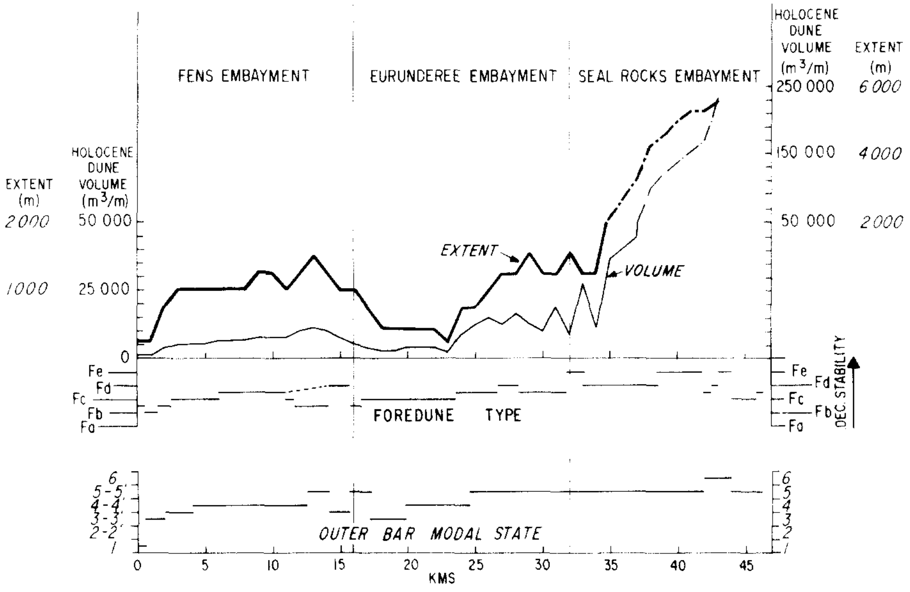


Fig.9. Morphometric parameters for 47 km of the Myall Lakes (Fens, Eurunderee and Seal Rocks embayments; see Fig.1 for location), illustrating modal outer bar state (utilising Short's (1979b) classification), foredune type, and dune volume and extent.

flow disturbance, very low potential wave and aeolian sand transport and small foredunes. Landward dune formation is limited to non-existent.

Dynamic and morphologic variations

Natural variations in the level of wave energy and sediment size and abundance on beaches, means that in practice, our classification of high-energy dissipative beaches and low-energy reflective beaches represents only a percentage of existing beach environments. Here we extend the classification to include variations in wave energy, grain size and sediment abundance. Furthermore, the absolute size of foredunes and landward dune systems is further influenced by three primary environmental variables — regional wind velocities, grain size, and coastline orientation or exposure to dominant onshore winds. The role of these factors are also briefly discussed below.

Variations in wave energy — grain size and abundance

It is possible for dissipative beaches to exist in modal low wave energy conditions, where sand is very fine and/or very abundant. Overall beach-surfzone gradients tend to be lower, and intertidal mean beach width may be greater. Because of the low wave energy, sediment is not as readily transported to the beach over time. In addition, aeolian sand transport is less than on higher energy dissipative beaches, as the water table commonly lies very close to the beach surface, and threshold velocities are accordingly higher (Hesp, 1980). Beach-dune erosion is rare. Foredunes are thus of moderate size, very stable and well-vegetated, and topographically very regular. Dune transgression is non-existent.

Intermediate beaches may exist in high wave energy environments where the sand size is medium-coarse. Such environments display high susceptibility to beach-dune erosion, consequently foredunes are morphologically diverse and potential dune transgression is high.

Reflective beaches may exist at a range of energy levels and grain sizes. They may exist in fine sand environments where wave energy is very low (e.g. estuarine beaches), or in relatively high wave energy environments where sand is coarse to very coarse. Very low wave energy or fine-grained reflective beaches tend to have lower berms and hence lower beach gradients, while high-energy or coarse-grained beaches have the steepest beach faces. In most cases, potential sand transport is minimal and foredunes are usually small. The latter may vary where the coastline has been stable over a long period of time. On such coasts where single foredunes back the reflective beach the foredune may be of moderate size.

Wind energy and grain-size variations

The rate of sand transport is proportional to the third power of wind speed. Thus the greater onshore wind velocities, the greater the potential sand transport, and the larger the foredunes (assuming there is an available sediment source, and vegetation is present to trap sand). However, whilst the absolute size of dune systems depends, in part, on the magnitude of regional winds, the variation in relative size between dunes forming in the lee of reflective beaches and those forming in the lee of dissipative beaches should be maintained (see e.g. Jennings, 1957).

The degree of exposure to dominant onshore winds, determined by the orientation of the coast, may produce local variations in aeolian sand transport. The Myall Lakes embayment discussed above (Fig.7) is one such system which is typical of many zeta-curved embayments in N.S.W. which towards the north become more exposed to onshore southeast storm winds. Here a proportion of the variation in dune *volume* between lines 1, 2, 3 and lines 4, 5, 6 must be due to exposure to onshore winds. However, we believe that although exposure is an important variable, beach morphology, gradient and width are far more important in determining the rate of landwards aeolian sand transport (Fig.9). Several modal reflective beaches in N.S.W. and South Australia which have the same orientation (i.e. face southeast or southwest respectively) as modal dissipative beaches have small foredunes. Beach gradient, morphology and width thus dominate over wind exposure in determining potential sand transport and dune volume.

In general, aeolian sand transport threshold velocities will rise as mean grain size increases (Bagnold, 1941). Thus, other factors being equal, aeolian sand transport and potential dune size will increase with decreasing sand size.

PART C. IMPLICATIONS FOR GLOBAL WAVE AND WIND ENVIRONMENTS

Wave—wind interactions and beach—dune morphologies

The role played by regional wind and wave environments (Davies, 1980) and resultant beach morphology and potential aeolian sand transport are outlined in Table IV. The table lists those wave—wind environments found in southeast Australia [west coast swell, east coast swell and trade wind (seasonally)] as well as the remaining global wave environments (Davies, 1964) (storm wave, monsoonal and protected). Onshore wind energy is combined with beach type to indicate the relative levels of aeolian sand transport associated with various combinations.

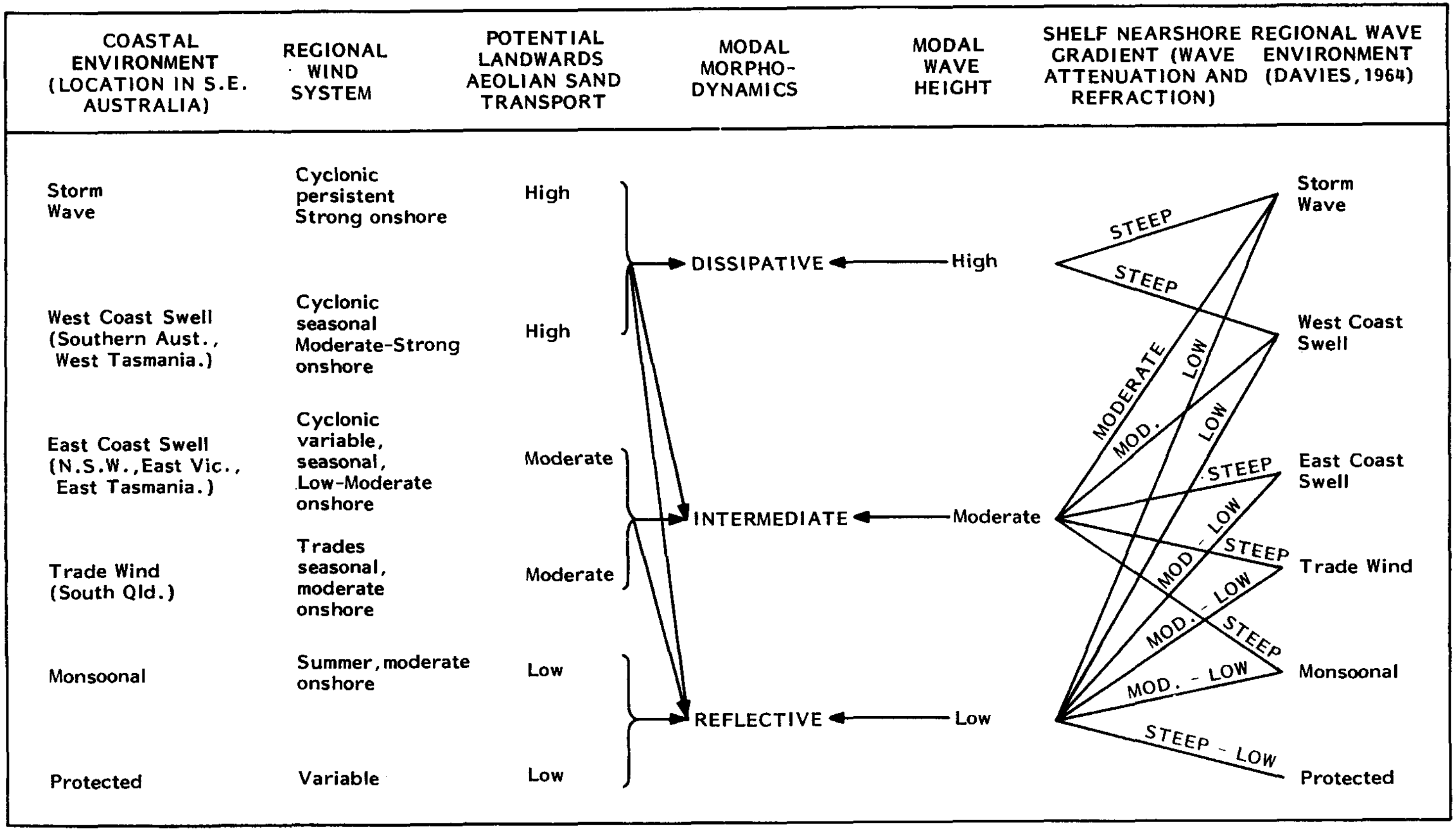
Two examples of the relative role of breaker wave energy, beach and foredune morphodynamics and extent of transgressive dunes are given in Figs.8 and 9. Note that in each embayment there exists a longshore gradation in breaker wave energy resulting from differential wave attenuation and refraction (see Fig.2 for loss of wave power). As a consequence of this spatial variation, the beach-surfzone adjusts accordingly, ranging in the Coorong from high-energy dissipative to low-energy intermediate, and in Myall Lakes embayments from low-energy reflective to moderate to high-energy intermediate—dissipative. The foredune morphology and stability closely parallel the beach morphology. Foredune stability varies from moderate on the high-energy dissipative beaches (e.g. Coorong I) to low on the high-energy intermediate beaches (e.g. Coorong II) to high on the low-energy intermediate and reflective beaches (e.g. Coorong III and lower Fens).

Even more dramatic is the impact through the Holocene of dune transgression within the embayments, with the extent and volume of dunes reaching a maximum in lee of the moderate to high-energy intermediate—dissipative beaches, and a minimum in lee of reflective beaches. Note that although in the Myall Lakes embayments the higher energy ends are aligned perpendicular to the dominant onshore southeasterly winds, and dune volume may be equated with exposure, in the Coorong the reverse is true. In the Coorong example, *as the beach becomes more perpendicular to the dominant onshore westerly winds, foredune stability increases and dune transgression decreases*. This and similar examples in southeastern Australia (e.g. North Cronulla, N.S.W., South Canunda, S.A.) add weight to the greater importance of the level of wave energy in determining beach and foredune instability and initiating dune transgression. While exposure to dominant onshore winds will obviously increase potential aeolian sand transport, our investigations have indicated that at present on moderate to well-vegetated dune systems *initiation* of major instability and dune transgression by wind is minimal.

Another important factor in favouring large dune volumes in lee of high-energy beaches is the greater sand transporting ability of these waves, resulting in more marine sand being delivered to the beach-surfzone either from offshore or alongshore.

TABLE IV

Regional wave, wind, beach interactions



COASTAL ENVIRONMENT (LOCATION IN S.E. AUSTRALIA)	REGIONAL WIND SYSTEM	POTENTIAL LANDWARDS AEOLIAN SAND TRANSPORT	MODAL MORPHO-DYNAMICS	MODAL WAVE HEIGHT	SHELF NEARSHORE GRADIENT (WAVE ATTENUATION AND REFRACTION)	REGIONAL WAVE ENVIRONMENT (DAVIES, 1964)
Storm Wave	Cyclonic persistent Strong onshore	High	DISSIPATIVE	High		Storm Wave
West Coast Swell (Southern Aust., West Tasmania.)	Cyclonic seasonal Moderate-Strong onshore	High				West Coast Swell
East Coast Swell (N.S.W., East Vic., East Tasmania.)	Cyclonic variable, seasonal, Low-Moderate onshore	Moderate	INTERMEDIATE	Moderate		East Coast Swell
Trade Wind (South Qld.)	Trades seasonal, moderate onshore	Moderate				Trade Wind
Monsoonal	Summer, moderate onshore	Low	REFLECTIVE	Low		Monsoonal
Protected	Variable	Low				Protected

On a global scale, the largest dunes occur in lee of high-energy dissipative—intermediate beaches exposed to onshore mid-latitude westerlies e.g. west coast of Tasmania, New Zealand, South Africa, U.S.A.; moderate dune development is characteristic of moderate energy intermediate beaches particularly along east coast swell and trade wind environments e.g. east coasts of Australia, New Zealand, South Brazil, Argentina. Low dunes are associated with low wind velocities and reflective beaches of the tropics and polar regions and all other regions.

CONCLUSION

In evaluating both the morphodynamics and Holocene evolution of sandy beach systems we must consider the contribution of the major energy sources — waves and wind, their transformation across the coastal zone, and the work they accomplish in transporting sediment. In this paper the genetic relationships are identified that link breaker wave height to beach-surfzone morphodynamics and in particular foredune stability. This in turn has consequences for the extent and type of dune transgression (see Table III). The role of regional wind and wave regimes are also considered in Table IV. The classification therefore provides both a method for readily identifying and classifying meso- and mega-scale beach and dune systems; and a starting point for fuller investigations of particular sites or environments.

The distinctive nearshore, surfzone, beach and dune morphologies associated with dissipative, intermediate and reflective beaches lend themselves to application in interpretation of palaeobeach-dune systems. Further the geographical distribution of the systems and their association with specific wave, wind and shelf environments permits fuller interpretation of auxiliary paleo-environmental parameters. While a great deal of work is still required to reconstruct an accurate geological model of these environments first approximation of the likely sequence and extent of these environments can be inferred from the nature and scale of the characteristic beach-surfzone and dune forms (e.g. Figs.4, 7, 8 and 9).

ACKNOWLEDGEMENTS

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APPENDIX

A classification of foredune morphology (Hesp, 1981)
Fa. Gently undulating, topographically continuous, very well vegetated (90—100% cover) foredunes.
Fb. Scarped Fa foredunes and/or with small scale (one to tens of metres) unvegetated troughs, hollows and linear-concave sand patches, local crestal instability and minor lateral vegetation density variation, 75—90% cover.
Fc. Hummocky foredunes with lateral topographic variation of small to moderate size, non-vegetated to partially vegetated blowouts, sand patches — sheets (particularly stoss faces) with vegetated concave stoss faces, crests, semi-discrete ridges and lee faces. Vegetation cover 45—75%.
Fd. Topographic variability pronounced. Moderate-large scale blowouts, sand sheets and deflation basins interspersed with partially vegetated ridges, mounds and depressions. Open vegetation cover, 20—45%.
Fe. Remnant knobs and mounds, large-scale arcuate deflation basins/blowouts and sand sheets. Vegetation cover 5—20%.

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