

# The Sedimentology and Stratigraphy of a Cuspate Foreland, Southwestern Australia

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## ABSTRACT

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The Holocene sedimentary deposit of the Rockingham-Becher plain in southwestern Australia provides a case study of cuspate foreland geometry, stratigraphy and origin, useful for stratigraphic geology. Sedimentation occurs in a mixed carbonate-terrigenous setting within a wave-dominated, or wave-activated, bathymetrically complex coastal zone. Eroded remnants of ancestral Pleistocene limestone ridges and depressions have had a major control on the distribution of wave energy and Holocene sedimentation. The sedimentary environments include an inter-related array of basin, (seagrass) bank, beach and beachridge/dune facies. With progradation and shoaling there has developed a relatively simple stratigraphy within the foreland. The Holocene deposits form a large scale lensoid package of sediment, cuspate in plan, that records a history of shoaling from basin, through bank, to beach and dune. The lensoid accumulation is plastered on, or abuts, a hinterland of Pleistocene limestone, and its apex is located near (and is influenced by), the Pleistocene limestone (barrier island) ridge to seaward. In the stratigraphic record this cuspate foreland system would appear as a discrete lensoid package of sediment, with an upward-shoaling stratigraphic sequence, and would appear lithologically distinct from its surrounding rock units.

**ADDITIONAL INDEX WORDS:** *Cuspate foreland, Holocene marine banks, Holocene coastal stratigraphy, coastal southwestern Australia.*

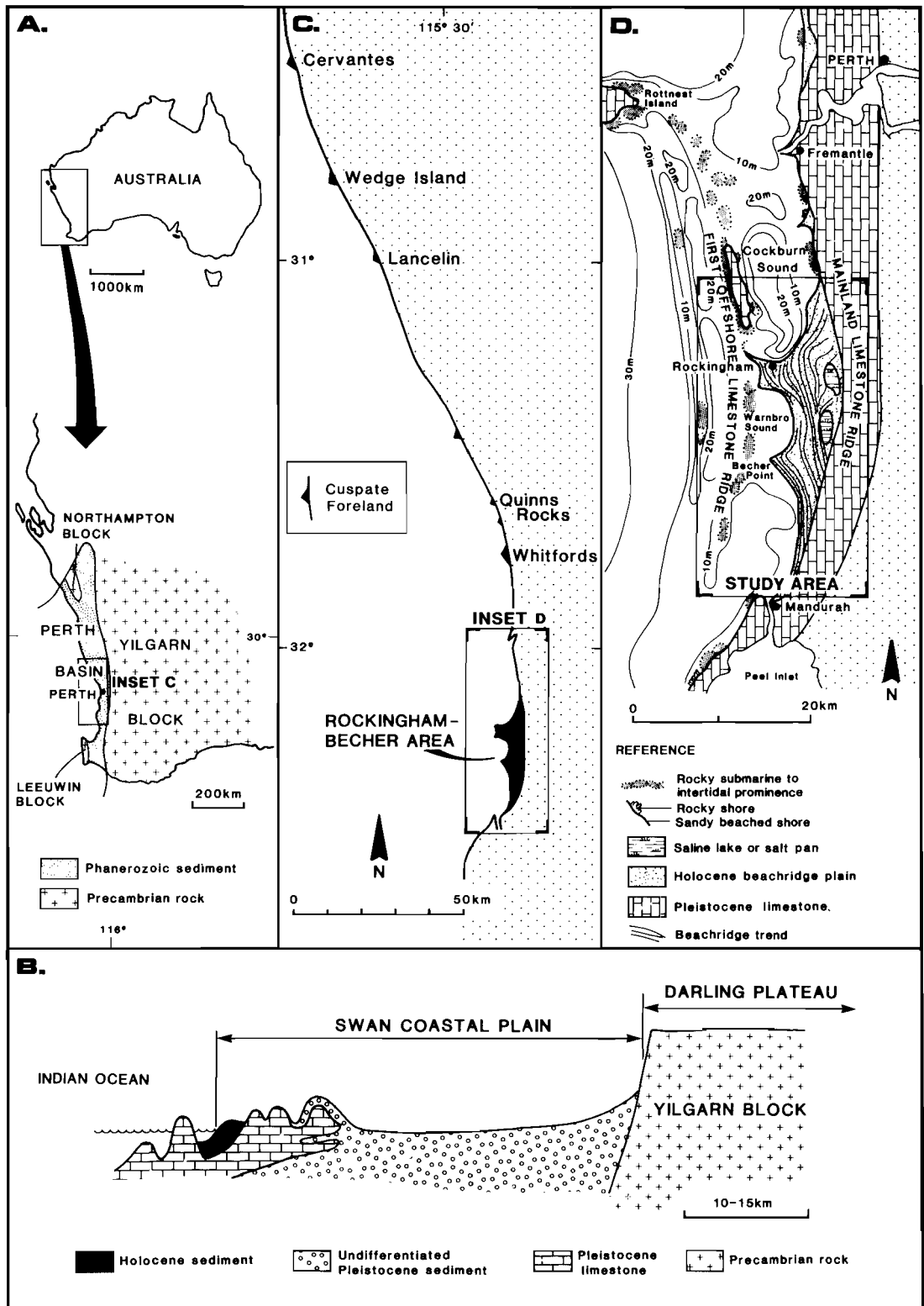
## INTRODUCTION

Cuspate forelands, and their related landforms, cuspate spits, are sandy low coastal terrains, triangular in plan, projecting as a point, or promontory, or large-scale cusp into marine, estuarine or lake environments (GULLIVER, 1896; KING, 1972; DAVIES, 1972; ROSEN, 1975; CARTER, 1982). Cuspate forelands have been described from many places around the globe, and the literature indicates that most are associated with deltas, tombolo settings, or spit/barrier coasts (GUILCHER and KING, 1961; ZENKOVICH, 1959, 1967; HOYT and HENRY, 1971; YASSO and FAIRBRIDGE, 1968). Indeed, the variety of coastal settings within which cuspate forelands occur, and the variety of stratigraphic sequences described to date within cuspate forelands reflect their diverse origins (JOHNSON, 1919; FISHER, 1955; RUSSELL, 1958; HEY, 1967; BIRD, 1969, 1985; KRAFT, 1971; HIGH, 1975; MOSLOW and

HERON, 1979; KRAFT *et al.*, 1979; KRAFT, 1985; PITMAN, 1985).

Much of the work to date on cuspate forelands has been geomorphological, dealing with the shape and genesis of the subaerially evident part of the forelands. Only a small number of studies concentrate on their stratigraphic evolution. The subaerially evident portion of a cuspate foreland, however, usually is only a thin sedimentary capping to a more extensive and volumetrically more important submarine sediment accumulation. It is in this aspect, the submarine geomorphology, stratigraphy and sedimentary history, that requires classification and highlighting in order to interpret origins of cuspate forelands. It is our view, therefore, that the classification, and interpretation of the origin of cuspate forelands, if it is to be of use to stratigraphers and Quaternary coastal geomorphologists, should be based more firmly on their underlying stratigraphy, which would reflect their preceding submarine accretion history.

Where the stratigraphy of cuspate forelands is described in the literature, the forelands are



usually from deltaic and barrier island settings. The stratigraphy of cusplate forelands in tombolo and other coastal settings generally is not well documented. Yet these latter systems are important geologically, because if they are present in the stratigraphic record, they may occur either as isolated, discrete, lensoid bodies, perhaps quite distinct from, and in unconformable contact with the surrounding stratigraphic sequence, or they may occur as a series of overlapping or coalescing lenses with a recurring internal stratigraphy. It should be possible, therefore, to recognise ancient cusplate foreland sequences from their geometry, to infer their mode of origin from their stratigraphy, and to interpret their palaeo-geographic setting from their stratigraphic and sedimentologic information.

Along the southwest coast of Australia there are a series of cusplate forelands (SEARLE and SEMENIUK, 1985; WOODS *et al.*, 1985; SEMENIUK and SEARLE, 1986; SEARLE *et al.*, 1988). The largest cusplate foreland system in the region occurs in the Rockingham-Becher area (Figure 1), which contains two juxtaposed cusplate forelands, essentially a twin system. Information on the sedimentary system and stratigraphy of this area, as yet largely undescribed in the international literature, is a useful addition to models of cusplate foreland development because of the overall stratigraphic setting of the sequence within a limestone barrier island, ridge-and-depression topography. Here, relatively small, offshore barrier islands and reefs of limestone interact with the wave pattern, and together with the diverse sources of sediment, influence the development, geometry and stratigraphy of the forelands. As a result, a foreland system is developed with a distinct geometry, a distinct stratigraphic relationship to surrounding basement units, a diagnostic internal stratigraphy, and a specific mode of origin.

This paper provides information on the distinctive features of the cusplate forelands in the

Rockingham-Becher area and provides insight into the relationships and origins of similar lensoid stratigraphic units that may have formed as accretionary sedimentary bodies in the lee of small barrier islands.

## REGIONAL SETTING

The study area, centred on the Rockingham-Becher plain, occurs along the seaward portion of the Swan Coastal Plain, a coastal lowland which is the Quaternary surface of the Phanerozoic Perth Basin in subtropical southwestern Australia (PLAYFORD *et al.*, 1976; BIGGS *et al.*, 1980). The Rockingham-Becher plain occurs in coastal sector 3 of southwestern Australia (SEARLE and SEMENIUK, 1985). The nearshore to onshore geomorphology and bathymetry of this entire sector is complex, and is dominated by a series of shore-parallel submarine to emergent Pleistocene aeolian limestone ridges and associated depressions. There are also significant sites of Holocene deposits of mixed terrigenous and carbonate sediment forming discrete, shore-normal accumulations (Figure 1).

The oceanography of this coastal area is wave dominated and microtidal, with a 0.4 m tidal range (HODGKIN and DILOLO, 1957; STEEDMAN and CRAIG, 1983; SEARLE and SEMENIUK, 1985). Wave action and wind-generated currents are principal agents in littoral drift, submarine cross-bank sediment transport, and in the erosion and transport of sediment from the Pleistocene limestone ridges. The prevailing waves all year are oceanic swell deriving from between west and southwest, supplemented in summer by southwest wind waves developed by seabreezes.

In winter, storm waves, which approach mainly from northwest and west, also have a significant influence on coastal processes. The complex nearshore bathymetry dampens, refracts and diffracts the swell developing complicated convergence and divergence of wave orthogonals. Locally-generated wind waves are of shorter period and wavelength, and are less modified by the bathymetry. The dominant sand-shifting winds in the area are southwesterly seabreezes which are responsible for onshore aeolian transport and dune (blowout) formation.

Figure 1. Regional setting of the Rockingham-Becher plain. (A) Setting in the Perth Basin (map after PLAYFORD *et al.*, 1976). (B) Schematic cross-section of the Swan Coastal Plain showing relationships of Holocene coastal sediments to the Pleistocene limestone ridges. Veneers of Holocene sediment overlying mainly Pleistocene sequences are not shown in the illustration. (C) Distribution of Holocene cusplate forelands along the coast of southwestern Australia. (D) Geomorphic setting of the Rockingham-Becher plain. (Facing Page).

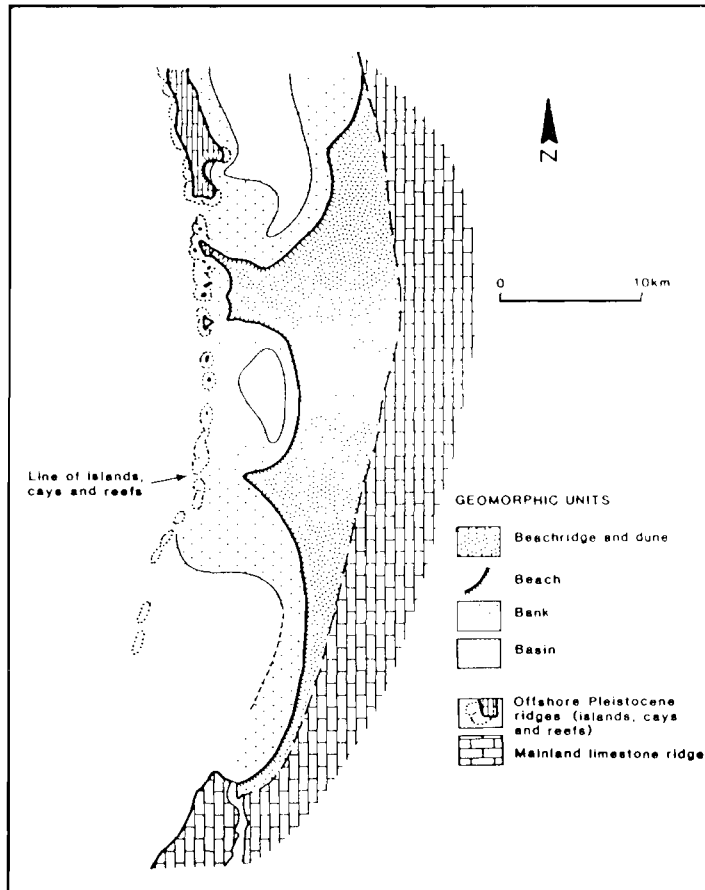


Figure 2. The geomorphic components of the cusate foreland in the study area.

### COASTAL GEOMORPHOLOGY AND SEDIMENTARY FACIES

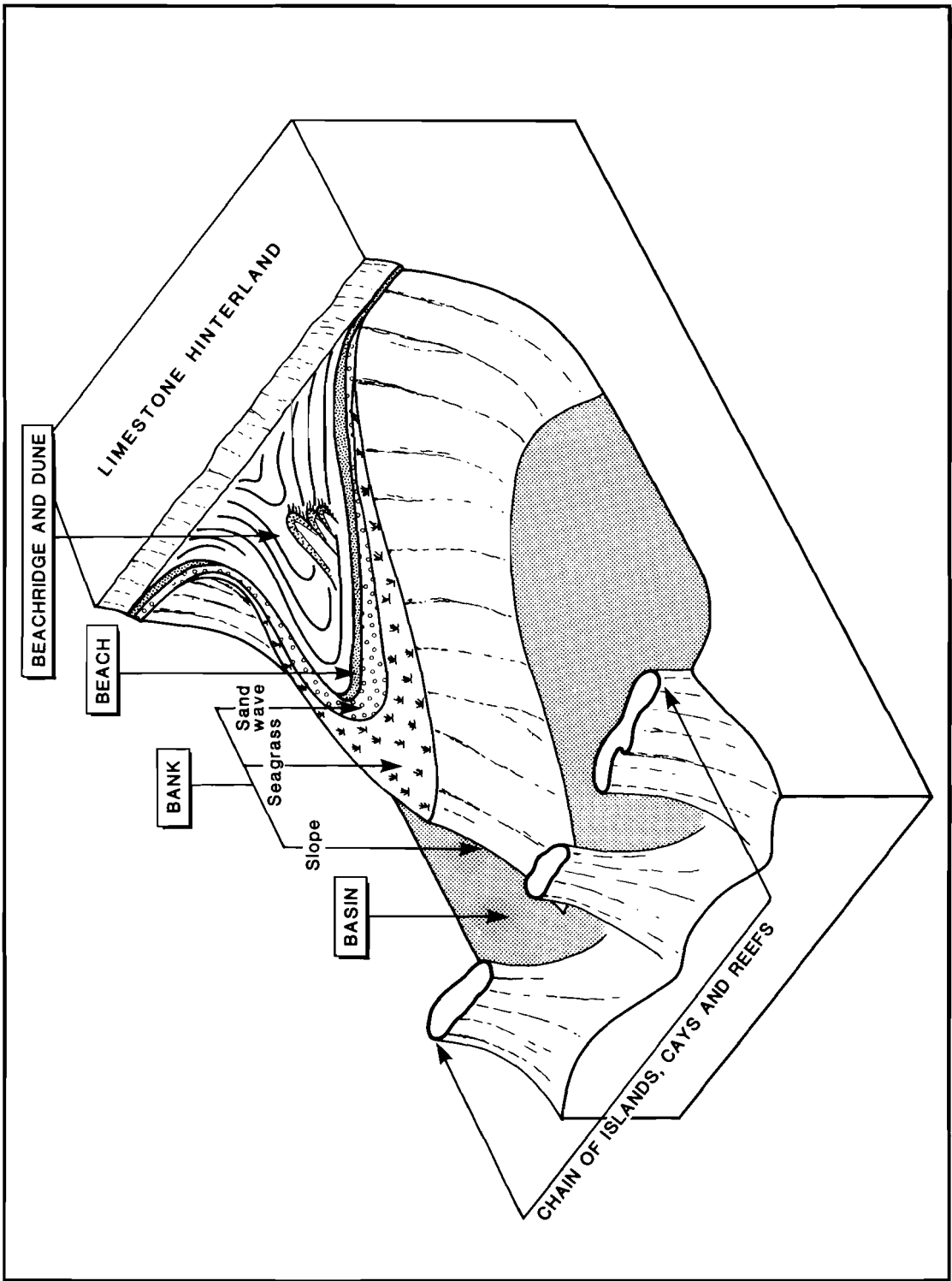
A system of parallel Pleistocene limestone ridges comprise the mainland shore (or hinterland) in this area, and form offshore islands, cays and rocky reefs (Figure 1). The ridge along the mainland shore forms a topographic barrier between the inner shelf and the low coastal plain further landward. Those ridges which form the offshore islands, cays and reefs vary from continuous to discontinuous, and have relief from a few metres to in excess of 80 m above the floor of adjacent depressions. The Holocene deposits span the depression between the mainland and the first offshore ridge to form discrete, shore-normal submarine banks, locally topped by extensive, cusate beachridge

plains (or forelands). The beachridge plains in the study area comprise two cusate forelands that have laterally merged to form a large sedimentary complex, essentially a twin cusate foreland system. The Holocene sedimentary environments in the sites of accumulation include inter-related basin, seagrass bank, beach and beachridge/dune facies, and are described in more detail below (Figures 2 and 3).

#### Basins

Basins are the deep water areas of 16-25 m depths, flanked by banks to the east, north and south, and by the offshore ridge to the west.

Figure 3. Idealized diagram showing distribution of lithofacies across a cusate foreland. (Facing Page).



Basin floors lack bathymetric features and seagrass cover, and generally consist of grey, bioturbated carbonate muds, or, in more exposed localities, lighter grey, fine to medium sand. The low energy deep water basins accumulate the slowly settled fine sediment entrained in the water column from the more energetic environments up-slope.

### Banks

Banks are submarine features, with up to 20 m relief above basin floors, composed of Holocene sediment that extend across the marine depressions to form submarine promontories and narrow fringing platforms. There are two main banks in the area and these extend east-west from the mainland towards the first offshore ridge to form the main foreland terrain. Between the two main bank axes there are narrow fringing banks or platforms (about 100 m wide) peripheral to the basins. Seaward of the surf zone the surfaces of banks slope gently to depths of about 6 m, below which they slope more steeply into the basins. Banks are surfaced by seagrass meadows and, to landward, sand flats. Sandy shoals also are developed and locally are emergent.

The bank facies includes seagrass-covered lithotopes, sand wave lithotopes and slope lithotopes. Sediments accumulating under seagrass meadows are grey, bioturbated to root structured, sand and shelly sand, varying to muddy sand and shelly sand, composed of skeletal material with variable seagrass detritus, fibres and carbonate mud. The sediments also contain quartz and lithoclasts adjacent to limestone outcrops. Sedimentary processes in the seagrass-covered lithotope include *in situ* skeleton production and its accumulation in the seagrass meadows, bioturbation by fauna, accumulation of seagrass material, cross-bank transport by waves and currents on local seagrass-free surfaces, and the trapping, binding, and baffling of sediment by seagrasses.

Sand wave surfaces occur immediately seaward of the inshore zone, up to the margin of the seagrass biotopes. The sediments are well sorted medium sand. Migrating sand waves and megaripples, up to 1 m amplitude, dominate the surface, and form cross layered sedimentary structures.

The slope lithotope occurs to depths where the

slopes of the banks merge with the basin floors. The sediments are well sorted, grey, medium to fine sand, compositionally similar to the bank lithotope, from which they are derived, but without large skeletal fragments. Sediments on the lower slopes are fine sand and structureless; those on the upper slope are medium sand with slope-parallel lamination. Transport in this environment involves downslope movement of sediment impelled over the bank edges by cross-bank currents. The steep slope, and the decrease in wave and current energy, ensure that transport is unidirectional into the basin.

### Beach Zone

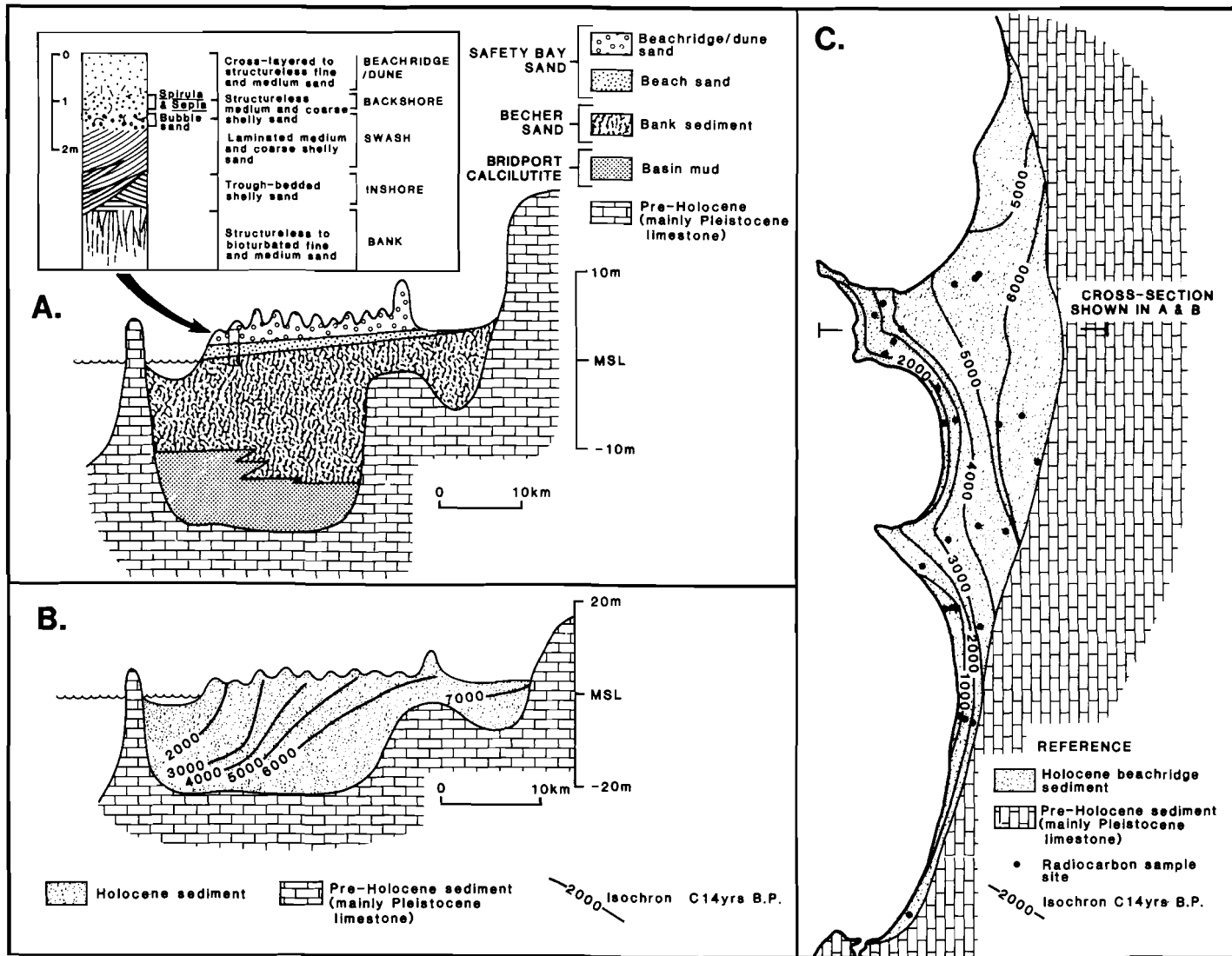
Beach sediments are medium to coarse skeletal and lithoclast carbonate sand with minor quartz. Sedimentation on the beach includes wave and current transport, swash zone processes, storm erosion and accumulation, and aeolian transport. The beach environment can be subdivided into several zones, viz., backshore, swash and subtidal inshore (SEMENIUK and JOHNSON, 1982), and sediments show variation in grain size and structures that reflect the processes operating therein. The sequence of sediments and structures are: (1) horizontal to seaward-dipping, layered, medium sand in the backshore; (2) seaward-dipping, laminated, medium to coarse shelly sand in the swash zone, with bubble sand in the upper swash; and (3) cross- and trough-layered, medium to coarse sand and shelly sand in the inshore zone.

### Beachridge and Dune Plain

The active beachridge/dune facies adjoins the shore, and forms by aeolian transport inland from the beach. The sediments are well sorted, medium sand composed of skeletal fragments, lithoclasts and quartz. Large scale cross layering is the dominant sedimentary structure, except where vegetation has prevented the formation of structures or rootlets have disrupted them.

In plan, the prograded beachridge/dune plain of the study area has a well defined margin to the east where it abuts the mainland ridge, and

Figure 4. (A) Stratigraphy of the cusate foreland in shore-normal section (after SEARLE *et al.*, 1988). (B) Age structure of the cusate foreland in cross section (after SEARLE *et al.*, 1988). (C) Age structure of the cusate foreland system in plan (after WOODS and SEARLE, 1983; SEARLE *et al.*, 1988). (Facing Page).



a cusplate, or scalloped western margin (because of the juxtaposition of the twin, cusplate foreland systems). The surface is characterised by parallel, linear beachridges and intervening swales, stabilized by vegetation. However, there is local aeolian modification of the beachridges varying from minor sculpturing, to complete obliteration by reworking into blowouts and parabolic dunes.

### Geomorphic Evolution of the System

Holocene sediment accretion has been controlled by the supply of sediment and by the interaction of the shelf wave climate with the complex ridge-and-depression bathymetry (SEARLE, 1984; SEARLE *et al.*, 1988). Under the influence of prevailing swell and wind waves, there has been net northward sediment transport along the exposed seaward faces of the mainland ridge and the first offshore ridge. Where the offshore ridge sheltered the mainland shore, longshore transport diminishes as the offshore ridge gains prominence. As a result the littoral drift has accumulated in sheltered areas (*i.e.* a tombolo effect) behind the larger islands to form shore-normal submarine banks and recurved spits. This sedimentary material was supplemented by *in situ* skeletal production and erosion of Pleistocene limestone.

Additionally, the offshore ridge acts as a perforate barrier allowing a portion of the incident swell through gaps into otherwise sheltered depressions. Holocene sedimentation has been influenced by these loci of transmitted wave energy also to form the shore-normal submarine banks. Waves passing through breaches in the ridge divert sediment from the transport pathway on the seaward side of the ridge and impel it landward into the adjacent depression to form lobate submarine banks. Where bank lobes have accreted to an extent that they perturbate the swell wave pattern and disrupt the pattern of longshore transport on the mainland coast, they cause progradation of a sandy cusp from the mainland toward the advancing bank. When the bank and cusp meet, progradation of a beachridge plain across the bank surface is initiated and is centred on this bank-cusp axis. In contrast, the coastline between any two adjacent banks progrades more slowly. Coincident with bank accretion there is continuing erosion and widening of breaches in the offshore ridge

culminating in the reduction of the island chain to a series of submerged reef lines.

### STRATIGRAPHY

The Holocene sequence forms a large scale lensoid body resting on an unconformity that is cut into, or is coincident with the buried ridge-and-depression Pleistocene palaeotopography. The Holocene sediments abut a steep cliff cut into Pleistocene limestone along the mainland ridge, and pinch out against, or onlap, the Pleistocene limestone of the offshore ridge (Figure 4). In the depression between the two ridges the unconformity is marked by calcreted limestone with variable cover of (yellow) continental quartz sand. The main Holocene units in the area, in stratigraphic order, are (Figure 4):

- (3) beach, beachridge and dune sand (= Safety Bay Sand);
- (2) bank sediments (= Becher Sand); and
- (1) basin carbonate mud (= Bridport Calcutite), which occupies former depressions in the underlying palaeotopography and is the lowermost unit of the main Holocene deposits.

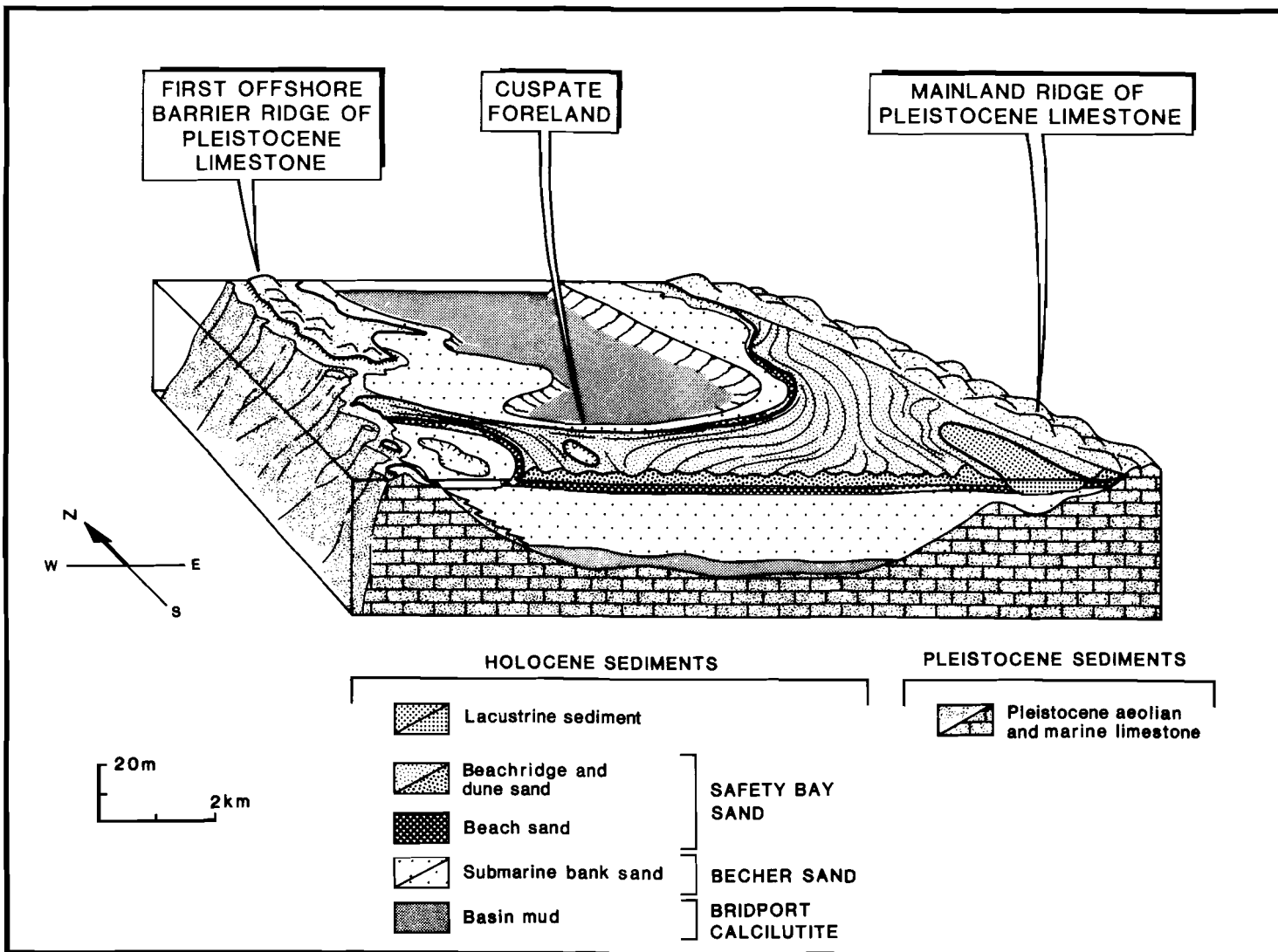
These units are described in more detail by PLAYFORD *et al.* (1976), SEMENIUK and SEARLE (1985, 1987) and SEARLE *et al.* (1988). Locally, there are minor rocky shore deposits along the margins of Pleistocene ridges, and thin estuarine deposits in former localised depressions; both of these are buried by younger Holocene units.

For stratigraphic and palaeo-environmental purposes the Safety Bay Sand further is subdivided into a small scale sequence of structures, lithology and grainsize, reflecting depositional gradients within the facies (SEMENIUK and JOHNSON, 1982; WOODS and SEARLE, 1983); the stratigraphic sequence is:

- (4) cross-layered to structureless beachridge and dune sand, with *Spirula* (rams horn shell), *Sepia* (cuttlefish bone) and *Ocyropode* (ghost crab) burrows localised near the base, grading down into
- (3) horizontal to seaward dipping, layered to disrupted medium sand (backshore unit),
- (2) seaward-dipping laminated medium to

Figure 5. Three-dimensional diagram illustrating the geometry and stratigraphy of a cusplate foreland and its relationship to the Pleistocene barrier limestone ridges. (Facing Page).





coarse shelly sand (swash unit) and locally preserved bubble sand, with *Donax* and *Glycymeris*, and

- (1) cross- and trough-layered medium and coarse sand and shelly sand (inshore unit).

The base of the sequence rests on the bank sediments of the Becher Sand.

The accumulated stratigraphic array of units in this area forms a large scale, lenoid package of sediment, cusate in plan, that records a history of shoaling from basin, through bank, to beach and dune. The lenoid accumulation is plastered on, or abuts, a hinterland of Pleistocene sediments, and its apex is located near (and is influenced by) the Pleistocene limestone (barrier island) ridge to seaward (Figure 5). Radiocarbon data from the sequence indicate that the cusate foreland system began accreting approximately 8000 C<sup>14</sup> yrs BP, and has steadily accumulated up to the present (SEARLE *et al.*, 1988). The configuration of isochrons within the cusate foreland system is shown in Figure 4.

## DISCUSSION AND CONCLUSIONS

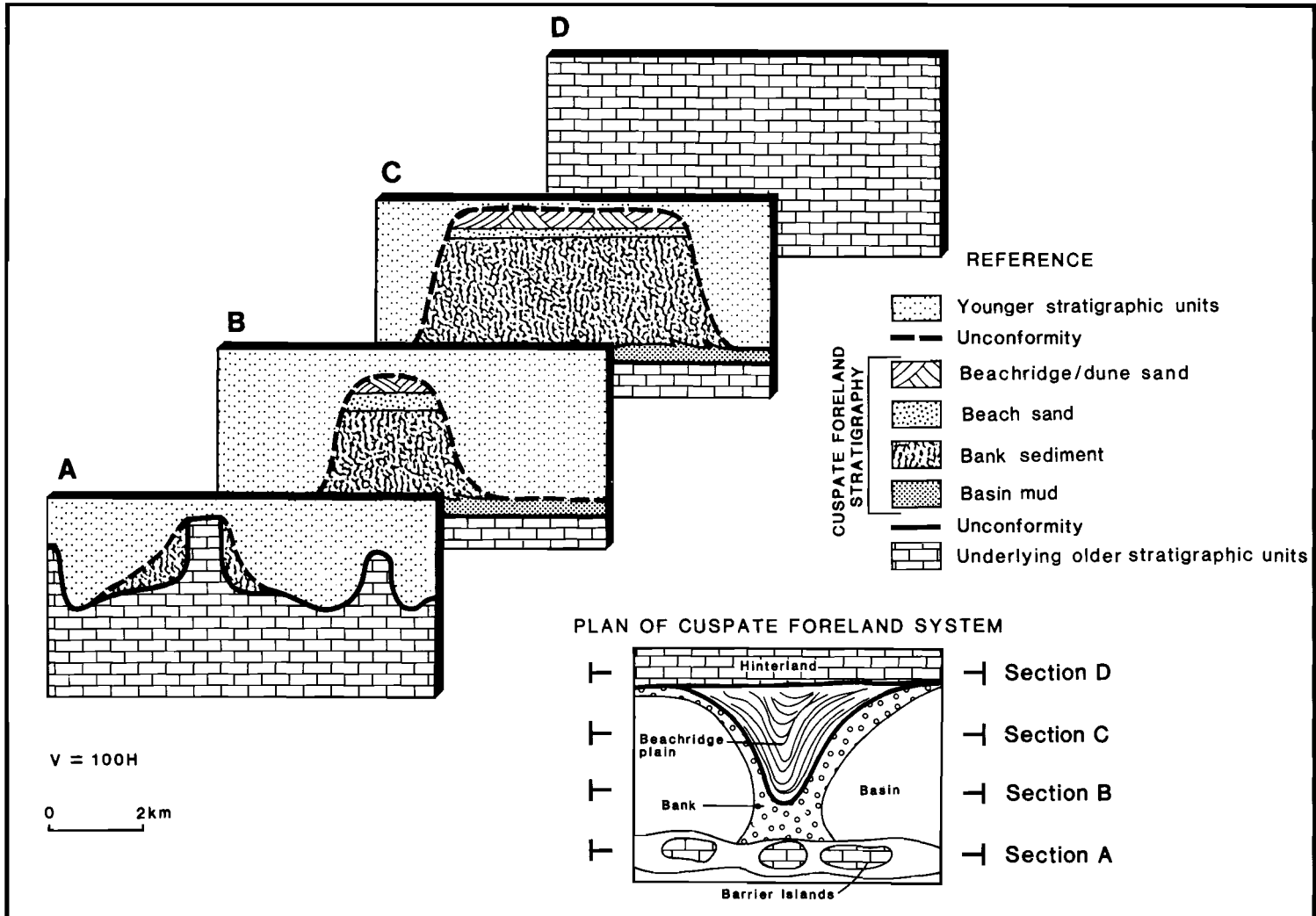
The Rockingham-Becher plain is significant for a number of reasons. Firstly, it is an example of seagrass bank sedimentation in cusate foreland setting. Secondly, the sedimentary system and stratigraphy are relatively simple since the area contains only a few sedimentary facies. Thirdly, the deposits preserve an interesting geometry, stratigraphy and history of Holocene sedimentation. Fourthly, since it is an example of wave-dominated, or wave-activated Holocene bank sedimentation in a bathymetrically complex coastal zone, the area serves as an additional model of cusate foreland genesis useful for stratigraphic geology and carbonate sedimentology.

The entire accreted sedimentary system of the Rockingham-Becher area probably can be classified as a carbonate complex, broadly similar to the Shark Bay seagrass sedimentary complexes (*cf.* DAVIES, 1970; HAGAN and LOGAN, 1974). However, the sedimentary system in the Rockingham-Becher area is distinctive in that the (seagrass) bank sedimentation within this bathymetrically complex system is developing discrete, large-scale, shore-normal sedimentary bodies, capped by cusp-shaped

emergent landforms (essentially cusate forelands), related to offshore barrier islands. In contrast, the seagrass bank sedimentation in Shark Bay, and elsewhere, frequently results in extensive, shore-parallel sedimentary accumulations in the form of prisms, wedges and ribbons, or sheets and mounds (MOLINER and PICARD, 1952; GINSBURG and LOWENSTAM, 1958; HAGAN and LOGAN, 1974; TURMEL and SWANSON, 1976). The Rockingham-Becher area also is distinct from other seagrass bank systems in that its sedimentary sequence is finally capped by an extensive beachridge/dune plain as the climax sedimentary unit. Thus the style of sedimentation and the coastal history of the study area contrasts with that of other areas of seagrass bank sedimentation such as Shark Bay, Florida, or the Mediterranean.

The stratigraphy of the Rockingham-Becher system is relatively simple, reflecting the microtidal setting and facies types of the area, and consists essentially of 3 sediment units accumulated in superposition. Each sediment unit represents a distinct environment of deposition. Comparisons with the stratigraphy of seagrass bank areas elsewhere may show similar lithology within the seagrass bank lithofacies, but a contrast in the stratigraphic units capping the entire sequence. For instance, the Shark Bay sequence begins with a carbonate mud which is succeeded by sandy to muddy sand seagrass bank lithofacies, similar to the seagrass bank lithofacies in the Rockingham-Becher area, but the capping units are sediments from hypersaline sublittoral environments or hypersaline intertidal environments (HAGAN and LOGAN, 1974). The seagrass bank sequences in Florida and the Mediterranean also are not capped by extensive, emergent lithofacies such as beachridge sand. Comparisons with cusate forelands described elsewhere from deltaic, tombolo, or barrier island settings also shows a contrast in stratigraphic style, in that the deposit at Rockingham-Becher consists of a distinct sequence of carbonate facies. Consequently, the sedimentary model derived from this area provides an important additional example of Holocene sea-

Figure 6. Idealised cross-section showing appearance of lenoid package of shoaling sediment, formed by sedimentation in a discrete cusate foreland, as it would appear in the stratigraphic record. (Facing Page).



grass bank sedimentation and stratigraphic evolution, and an addition to worldwide examples of types of cusate forelands.

The stratigraphic geometry of a cusate foreland system in this type of coastal setting [where sedimentary evolution has been strongly influenced by shore-normal bank growth set within a ridge-and-depression topography with limestone barrier islands] consists of a discrete, lensoid package of shoaling sediment. The lensoid body itself is contained within a depression between the two Pleistocene limestone ridges, and the site of accretion has been influenced (controlled) by the location of residual reefs and islands of the offshore limestone barrier ridge. In the stratigraphic record, this sediment body would appear as a discrete unit of limited extent and thickness (Figure 6), and given that as a carbonate unit it could be lithified early, its chances of preservation would be potentially high. Thus foreland sedimentary systems in the stratigraphic record, as typified by the Rockingham-Becher area, could be preserved as discrete, definitive lenses of carbonate rock perhaps quite lithologically distinct from the surrounding rock units.

Within the lensoid sediment body in the Rockingham-Becher area there is a distinct sequence of sedimentary units reflecting accretion from the deep water basins through seagrass-dominated bank and wave-dominated shoreface sedimentation, and finally to sub-aerial beachridge and dune accumulation. This sequence is an important indicator of the range of lithofacies in the sedimentary system, and of the type of geomorphic setting within which the sedimentary accretion took place. Other sequences, elsewhere in the Holocene, and in the stratigraphic record, may lack the specific environmental lithofacies of the Rockingham-Becher sequence, but comparable shoaling stratigraphy within the lensoid sediment package may be present thus giving clues to the existence of a buried former cusate foreland system. Certainly since cusate forelands are closely linked to wave-dominated environments, or at least to wave-activated environments, then the capping of beach and beachridge/dune sediments in the lensoid sediment package should be present. The submarine sequences may be a variety of lithofacies. However, a lensoid cross section, and a triangular

(or cusate) plan configuration should be present, especially for those sequences in a carbonate rock setting.

In summary, it is concluded that the Rockingham-Becher cusate foreland system is scientifically important. It provides a case example of the development of a distinct geomorphological feature which has a characteristic structure, and provides a case example of a stratigraphy which faithfully reflects its environment of deposition, its setting, and its history.

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□ RESUMEN □

Los depósitos sedimentarios holocénicos de la planicie Rockingham-Becher en suroeste de Australia proporciona un caso para el estudio geométrico, estratigráfico y origen de formas arenadas adelantadas útil para la geología estratigráfica.

La sedimentación es una mezcla carbonato-terrigeno aportada bajo la acción del oleaje o activada por el oleaje y presenta una batimetría compleja. Las calizas selictas del Pleistoceno tienen el control de la distribución de la energía del oleaje y de la sedimentación holocénica. El ambiente sedimentario incluye una cadena de depresiones interrelacionadas, bajos, playa y duna.

Los depósitos holocénicos presentan una acumulación de sedimentos con forma en planta apuntada y manifiesta la historia de la propagación del oleaje desde las depresiones, a través de los bajos hasta la playa y duna.—*Department of Water Sciences, University of Santander, Santander, Spain.*

## □ ZUSAMENFASSUNG □

Nacheiszeitliche Ablagerungen in Südwestaustralien ermöglichen eine Fallstudie zur Geometrie bogenförmiger Strandabschnitte (cusped forelands), ihrem Schichtaufbau und ihrer Entstehung. Die Sedimentationen finden in einem kontinentalen kalkhaltigen Ablagerungsgebiet an einem wellendominanten, morphologisch komplexen Küstenabschnitt statt. Erosierte Reste eines ehemaligen pleistozänen Kalkriffes in einem Senkungsgebiet sind die Haupteinflußgrößen für die Verteilung der Wellenenergie und der Sedimentationen. Das Sedimentationsmilieu im Becken wird durch Seegrassbänke, Strände und Dünen geprägt. Mit der Ausbreitung und Verflachung des Vorstrandes hat sich eine relativ einfache Schichtung ausgebildet. Diese nacheiszeitlichen Ablagerungen bilden ein großes, im Aufriß linsenförmiges Sedimentpaket, daß die Entwicklung der Verlandung dokumentiert. Die Ablagerungen sind landwärtig durch Kalkgestein überschüttet. Der Scheitel der Ablagerungen liegt seeseitig in der Nähe eines Kalksteinriffes. In der Schichtabfolge erscheint dieser Strandabschnitt als ein unstetes Sedimentpaket mit einer aufwärts abflachenden Schichtenfolge, die sich lithologisch vom umliegenden Gestein unterscheidet.—*Reinhard Dieckmann, WSA Bremerhaven, West Germany.*