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Pleistocene Coastal Palaeogeography in Southwestern Australia—Carbonate and Quartz Sand Sedimentation in Cuspate Forelands, Barriers and Ribbon Shoreline Deposits

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ABSTRACT

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The Yalgorup Plain is a well preserved late Pleistocene coastal plain in the Perth Basin, southwestern Australia. The carbonate and siliciclastic sediment sequences therein show that Pleistocene palaeo-coastal sedimentation was dominated by narrow beachridge plains developed as ribbon shoreline deposits and cuspate forelands behind offshore barrier limestone islands and rocky reefs. The key to interpreting the Pleistocene sequences and their sea level history lies in the Holocene models in the same region, especially in the geomorphology and stratigraphy of coast types such as barrier dunes, estuarine lagoons and large-scale cuspate beachridge plains and in the small-scale stratigraphy in beach/dune sequences, shoreface sequences, rocky shores and seagrass banks of the Holocene models.

The Pleistocene sequences contain 11 main sediment/rock types: (1) bioturbated foraminiferal calcarenite, (2) shelly/bioturbated calcarenite, (3) laminated shelly calcarenite/coquina, (4) laminated and cross-laminated marine calcarenite, (5) laminated to cross-laminated beach calcarenite, (6) cross-laminated to structureless aeolian calcarenite, (7) calcreted limestone, (8) indurated, bored limestone, (9) shelly calcilutite, (10) quartz sand, and (11) shelly mud. Sedimentation took place within a linear seaway between a hinterland ridge and two lines of offshore limestone rocky reefs. Evolution of the Yalgorup coastal plain took place in several stages related to sea level still-stands in the Pleistocene: (1) formation of an older Pleistocene limestone beachridge plain (Youdaland), within which there was shoaling from marine seagrass carbonate sedimentation to beach to beachridges/dunes; (2) accumulation of quartz rich coastal sand barriers (Myalup Sand Shelf and Myalup Sand Ridge); (3) formation of a younger Pleistocene limestone beachridge plain (Kooallupland) within which there was, again, shoaling from marine seagrass carbonate sedimentation to beach to beachridges/dunes.

The overall progressive accretion of the Yalorup Plain records, with subaerial interruptions: (1) sedimentation and progradation in a coastal setting partly behind offshore rocky reefs, (2) changes in style from cuspate foreland and shoreface accretion to coastal barriers, and (3) alternation in sedimentation from carbonate-rich to quartz-rich. Progradation was most marked under two sets of conditions: where carbonate production was active, with sufficient sediment production to promote progradation, and where there was shelter from open oceanic conditions, such as leeward of barrier ridges. When carbonate production was low, quartz sand from southern parts of the hinterland was reworked by coastal processes, and mobilised northwards to develop the shore-fringing, sand platform and a sandy barrier, but during this phase, there was no pronounced coastal accretion and progradation. The results of this study provide several insights: (1) the Quaternary history of the Perth Basin in southwestern Australia; (2) alternation of carbonate/siliciclastic sedimentation in general; (3) the control of the geometry of coastal sediment bodies by ancestral topography; (4) the longevity of limestone ridges in ancestral topography; and (5) the age structure of the Pleistocene coastal plains.

ADDITIONAL INDEX WORDS: *Pleistocene coastal palaeogeography; Swan Coastal Plain; southern Perth Basin; south-western Australia; cuspate foreland.*

INTRODUCTION

The Quaternary sequences of the Swan Coastal Plain, Perth Basin, southwestern Australia in their mixed carbonate and siliciclastic sediments provide a rich record of continental aeolian, coastal aeolian, shallow marine, estuarine, fluvial and alluvial fan deposition, accretionary coastal plain history, and climate history. It has long been recognised, for instance, that the shore-parallel limestone ridge system that occurs in this region may record the various shorelines of the Pleistocene and dune building phases during the Quaternary (FAIRBRIDGE and TEICHERT 1953; SEDDON 1972); and recently GLASSFORD and SEMENIUK (1990) pointed to the potential record of alternating glacial and interglacial events preserved in the siliciclastic aeolian deposits inland on the coastal plain. To date, however, most research on Quaternary coastal sedimentation and geomorphology in this region has been concerned with Holocene deposits or with description of Pleistocene stratigraphy and palaeontology (FAIRBRIDGE

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1950, 1953; FAIRBRIDGE and TEICHERT 1953; KENDRICK 1960; SEARLE and SEMENIUK 1985; PLAYFORD 1988). Few studies have attempted reconstructing Pleistocene palaeoenvironments and palaeogeography in accretionary settings, either at the local scale, or regionally, largely because the Holocene sequences were not yet fully documented to provide analogues. An exception is the study of KENDRICK *et al.* (1991), where the authors attempted to explain the change from predominantly siliciclastic sedimentation to carbonate-rich sedimentation within the Quaternary, but without recourse to interpretation of detailed sequences and lithofacies.

The key to interpreting the Pleistocene sequences in southwestern Australia lies in the Holocene models, and sufficient information on Holocene sequences now exists to attempt interpretation of the Pleistocene. This information includes: (1) classification and description of coastal types and regional processes (SEARLE and SEMENIUK, 1985); (2) description of geomorphology and stratigraphy of barrier dune, estuarine lagoon, and large-scale cuspate beachridge plain coast types (SEMENIUK and SEARLE, 1986a; SEMENIUK 1985; SEARLE et al 1988); and (3) description of small-scale stratigraphy in beach/dune sequences, shoreface sequences, rocky shores and seagrass banks (SEMENIUK and JOHNSON 1982, 1985; SEMENIUK and SEARLE 1985, 1987; SEARLE and WOODS, 1986; SEMENIUK 1994). It is only with such background information that Pleistocene coastal history in terms of palaeogeography, environments, eustasy, tectonism and climatic change can be unravelled.

This paper describes a well-preserved late Pleistocene coastal sequence between Mandurah and Bunbury in southwestern Australia (Figure 1), and, using a geomorphic and stratigraphic approach, attempts reconstruction of Pleistocene coastal palaeogeography and history. The patterns emerging show that Pleistocene coastal sedimentation was dominated by narrow beachridge plains developed as ribbon shoreline deposits and cuspate forelands behind offshore barrier limestone islands and rocky reefs. As such this paper provides information useful for understanding the long-term evolution of Quaternary coastal landforms in southwestern Australia and offers a model of coastal evolution useful for interpreting the geological record.

The study is based on data from stratigraphic sequences in drill holes, road cuts, quarries and excavations (Figure 1). Aerial photographs were used to map regional patterns, and traverses and drilling along 9 transects were conducted to confirm geomorphic/geologic phototones. Selected samples of each rock type in the stratigraphic sequences were sliced for thin section study, and selected shells (*Donax, Mactra, Katelysia,* and *Ninella*) from some profiles were submitted for radiocarbon analysis to confirm the Pleistocene age of some limestone units.

GEOLOGICAL SETTING

The study area is situated in southwestern Australia in a tract of country containing Pleistocene limestone within the seaward portion of the Swan Coastal Plain (MCARTHUR and BETTENAY, 1960; PLAYFORD *et al.,* 1976) and is set wholly in the Leschenault-Preston Sector (SEARLE and SEMENIUK, 1985) of the Rottnest Shelf coast (Figure 1). The subject of this paper is the Yalgorup Plain (formerly Yoongarillup Plain of MCARTHUR and BARTLE, 1980; redefined by SEMENIUK, 1990; currently in amendment), that is a Pleistocene to Holocene surface superimposed on a variety of fossiliferous limestones, aeolian limestone, and quartz sand units. This plain is bordered on the east by a prominent, linear, relatively higher ridge of aeolian limestone and quartz sand, and to the west by a relatively higher Holocene coastal aeolian ridge, or by Holocene estuarine lagoonal deposits.

Quaternary sediments underlie the Swan Coastal Plain and comprise the upper sedimentary fill of the Phanerozoic Perth Basin, which borders the Archaean Yilgarn Craton and has accumulated sediments since at least the Permian (PLAYFORD *et al.,* 1976). In this setting, Quaternary sediments under the Swan Coastal Plain are alluvial fan and fluvial deposits along the margin of the Precambrian craton, continental aeolian quartz sand in the longitudinally central part of the Plain, and coastal limestone and coastal aeolian quartz sand along seaward parts of the Plain (SEMENIUK and GLASSFORD, 1988). The limestone and quartz sand under the Yalgorup Plain thus are late Pleistocene deposits that abut and overlie older aeolian quartz sand formations of the central Swan Coastal Plain further to the east (Figure 1).

The limestone units in this area in the past have been referred to as the Tamala Limestone, but they are identified readily as distinct units in terms of lithology, stratigraphy and geography, and are treated here as separate formations. Within the plain, there also are elongate wetlands and lakes which appear mainly to be post-depositional geomorphic overprints on the limestone sequence; the origin of these lakes and wetlands is the subject of a separate study (C. A. SEMENIUK and SEMENIUK, 1995).

Offshore from the Yalorup Plain, the nearshore shelf is mostly an unconformity surface cut into Pleistocene limestone, with veneers of quartz sand, Holocene sediment, or minor reworked beach rock slabs (SEMENIUK and MEAGHER, 1981a; SEARLE and SEMENIUK, 1985; SEMENIUK and SEARLE, 1987a). Locally, particularly to the north of the study area, remnant shore-parallel ridges of Pleistocene limestone form offshore rocky reefs and islands (Bouvard Reefs; SEMENIUK, 1994). Inliers of these limestone ridges generally are buried by Holocene barrier dunes in the northern and southern parts of the study area. The occurrence of remnants of the limestone ridges has implication for controlling the development of cuspate forelands during the Pleistocene.

HOLOCENE MODELS

The Pleistocene sequences in this region are best understood if analogous Holocene sequences and their Quaternary settings are described first. The Holocene coasts directly applicable to interpreting the Pleistocene sequences are of two

* Footnote: There has been a problem with the concept, nomenclature and application of the term Yoongarillup Plain (MCARTHUR and BARTLE, 1980; SEMENIUK, 1990). At present, the term is being amended to Yalgorup Plain (SEMENIUK, 1995). For purposes of this paper, the proposed amendment will be used, rather than the incorrect current term.

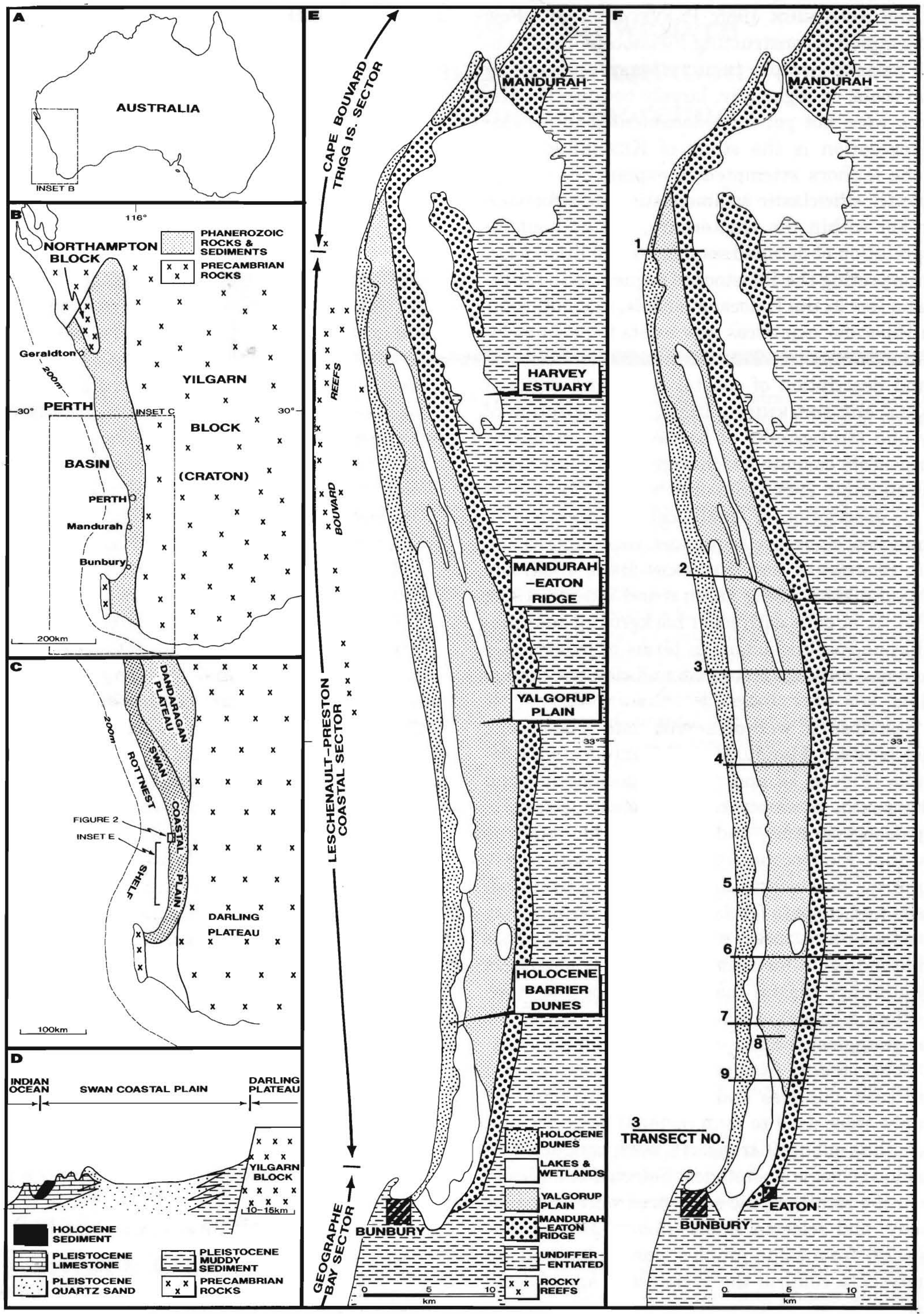


Figure 1. A, B, C & D: Location of study area in southwestern Australia in relationship to regional geology and geomorphology. E: Location of the Yalgorup Plain, offshore reefs and coastal sector boundaries. F: Location of drilling transects. Location of drill sites, quarries and road cuts are shown in Figure 7.

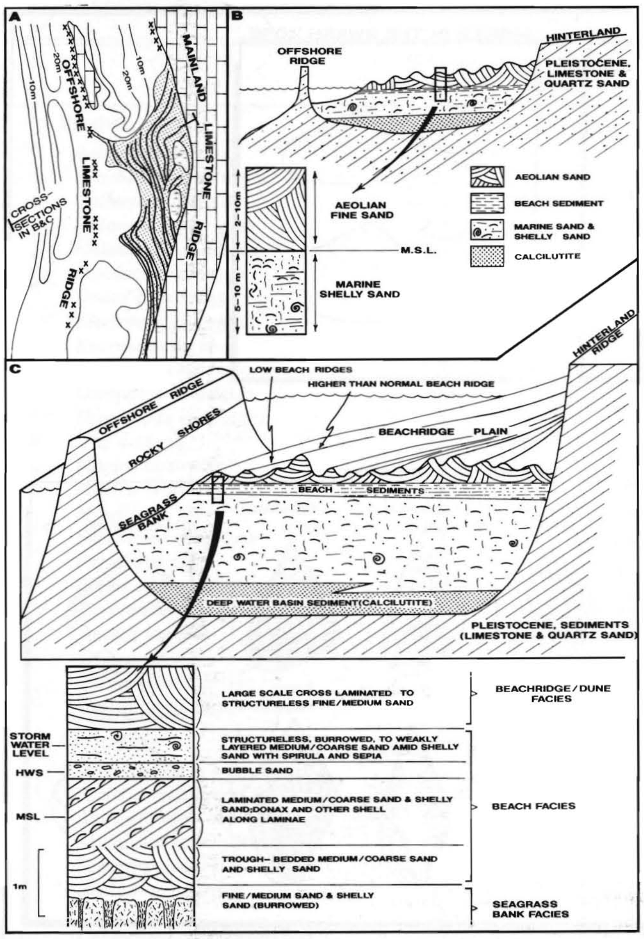


Figure 2. Elements of the Holocene model of geomorphology and stratigraphy at Rockingham-Becher. (A) Plan geomorphology showing the hinterland, the offshore barrier ridge, the cuspate to scalloped strandline of the low relief beachridge plain (after SEARLE *et al.*, 1988). (B) Idealised cross section of the system showing gross stratigraphic geometry and relationships, and the position of MSL determined by the large scale facies junction between aeolian and marine. (C) Idealised cross section of the system showing: more detailed geomorphic and stratigraphic relationships, detailed stratigraphy of the seagrass bank facies transition through beach facies, to beachridge/dune facies, and detailed sea level indicators.

types: (1) The Rockingham-Becher Plain (cuspate foreland with beachridges) developed leeward of an offshore barrier limestone ridge (SEARLE *et al.*, 1988; SEMENIUK, *et al.*, 1988); and (2) barriers, as exemplified by The Coorong (SPRIGG, 1952, 1979) and the Leschenault Peninsula (SEMENIUK, 1985).

Rockingham-Becher Plain

In the Rockingham-Becher area, there are well developed cuspate forelands with beachridge plains (Figure 2), the largest in southwestern Australia. The coastal zone is wave dominated, microtidal, with strong seabreezes. The ancestral Quaternary topography forming the backdrop to Holocene deposits is a conspicuous Pleistocene landform, consisting of shore-parallel ridges and depressions, which occurs in a belt along the seaward edge of the Swan Coastal Plain (MCARTHUR and BETTENAY 1960; SEARLE and SEMENIUK 1985). The ridges are composed of interlayered limestone and quartz sand (SEMENIUK and GLASSFORD 1988). With marine inundation, this landform is transformed into a series of offshore ridges, lines of islands and rocky reefs parallel to the shore, and a hinterland of limestone and quartz sand ridges, cliffed along the shore. With the last post-glacial marine transgression, the Holocene sea eroded the mainland, forming limestone rocky shores and isolating two series of ridges offshore (SEARLE, *et al.*, 1988). In this setting, Holocene sedimentation and coastal accretion has been confined to the linear depression between an eastern ridge forming the mainland shore, and a western ridge forming an offshore barrier. The elements of the Holocene system are summarised below (Figure 2). (1) There is a moderate-relief, aeolianite limestone ridge, mantled by quartz sand, that forms the hinterland; its western margin is the original (early) Holocene shoreline (SEARLE, *et al.*, 1988); (2) Offshore, an emergent to shallowly submerged shore-parallel, linear ridge forms islands and rocky reefs; subject to wave attack, the ridge is progressively breached and eroded. The islands have well developed shore platforms and a rocky shore suite of sediments and fauna (SEMENIUK and JOHNSON, 1985); (3) Between the hinterland and offshore ridge is a linear marine depression in which accumulates deep water carbonate mud (SEMENIUK and SEARLE, 1987b); (4) In zones of shelter leeward of the rocky reefs/islands, shallow water sedimentation and coastal progradation have taken place, forming submarine promontories/banks, and beachridge plains as cuspate forelands. The beachridge plain mostly has low relief, with ridge crests 2-3 m above MSL, reflecting gradual progradation of the beachridges, but locally there are lines of dune ridges up to 6 m high, and dune belts up to 10 m high, reflecting periods of higher-than-normal dune building; the modern shoreline is broadly cuspate, and beachridge trends on the plain indicate a history varying from simple to complex cuspate accretion; locally, progradation has been extensive enough to "capture" offshore islands; sediment in the banks, beaches and dunes is biogenic carbonate sand and gravel and exogenic lithoclast and quartz sand (SEARLE *et al.*, 1988).

Evolution of the system began with shoaling and prograding of a submarine bank, in most cases under a cover of seagrasses (SEARLE *et al.*, 1988). Resident fauna and flora associated with seagrass communities is rich in calcareous algae, molluscs, foraminifera, and burrowing benthos (SEARLE, 1984; LOGAN *et al.*, 1970), and these develop shelly, bioturbated carbonate-rich sediments. With accumulation, eventually the bank formed a submarine barrier/sill that spanned the marine depression between the offshore ridge and the shore and initiated progradation of beach, beachridge, and dune sediments across the bank top to form a cuspate, low-relief coastal plain. Where adjacent cuspate promontories have coalesced, a broad prograded plain capped by beachridges and dune ridges has formed. The various linear beachridge trends indicate the positions of former foredune shorelines (FAIRBRIDGE, 1950; WOODS and SEARLE, 1983). The sediments of the beach, beachridge and dune facies have distinc-

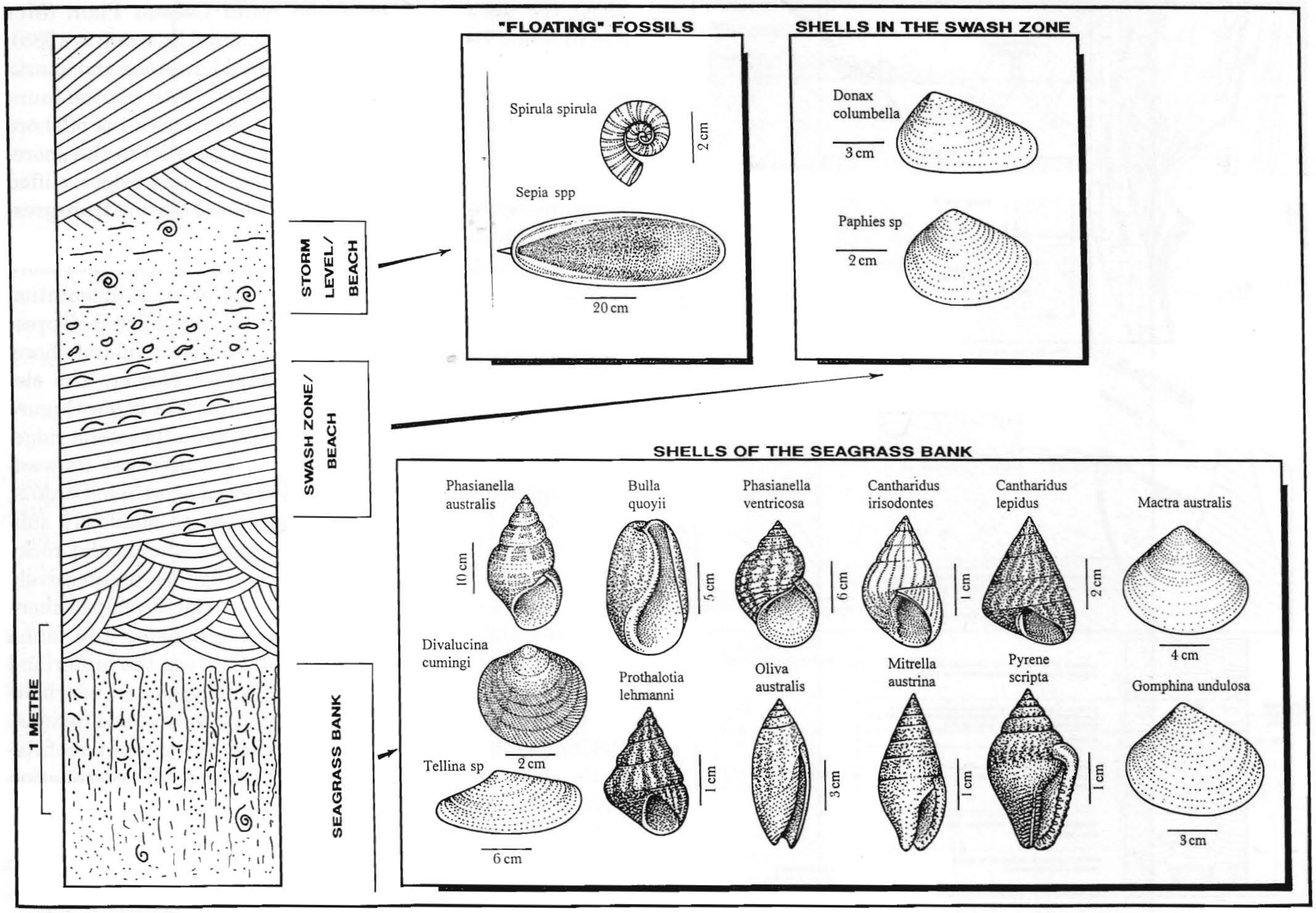


Figure 3. Idealised stratigraphy from seagrass bank facies, through to beachridge/dune facies, and the typical fauna.

tive sedimentary structure, lithology, and biota, as do the bank sediments (SEMENIUK and JOHNSON, 1982).

The evolution of the system is reflected in the distinct stratigraphy beneath the cuspate forelands and beachridge plains beachridge plains (Figure 2). From the top, stratigraphy includes: beachridge/dune sand, beach sediment, seagrass bank sediment, and basin sediment unconformably lying on Pleistocene carbonate and siliciclastic sediment.

Key features of this stratigraphy useful to interpreting Pleistocene sequences are as follow (SEMENIUK and SEARLE, 1985, 1987b; SEARLE *et al.,* 1988). (1) Deeper water basin sediments are (shelly) calcilutite (SEMENIUK and SEARLE 1987b). (2) The seagrass bank sediments are commonly sand and shelly sand, with molluscan fauna typical of seagrass assemblages; locally they are foramenifera-rich (*Marginopora*) (SEMENIUK and SEARLE 1985; SEARLE *et al.,* 1988). (3) The junction of the seagrass bank facies and the beach sequence is distinctively burrowed, with abundant vertical crustacean burrows 3-4 cm diameter, penetrating downwards for 50-75 cm (SEARLE *et al.,* 1988). (4) The beach sequence is composed of subtidal to low-tidal trough-bedded sand and shelly sand, low to mid-tidal swash zone sediment with seaward-dipping laminated sand and shelly sand containing *Donax,* high tidal bubble sand, and supratidal crudely layered, disrupted to structureless sand with diagnostic shells of *Spirula* and *Sepia,* and ghost crab (*Ocypode*) burrows; the sequence passes upwards into the cross-laminated to structureless beachridge sand (SEMENIUK and JOHNSON, 1982).

Key features of the lithology and biota of the seagrass bank to beach sequence are presented in Figure 3. The molluscan fauna of Holocene and Pleistocene seagrass assemblages are listed in Table 1. The cross-sectional shape of the Holocene seagrass bank to beachridge sediment body shows that the sequence abuts a former shoreline to the east, rests on deep water Holocene basin sediment, or unconformably on Pleistocene rocks and sediments, and pinch-outs down-dip to the west, essentially (overall) forming a ribbon up to 10 m thick with pinched-out margins (Figure 2). The seaward thinning may be abrupt, conforming to a steep synoptic surface of a seagrass bank.

The various facies and their interfaces provide useful sea level indicators that can be used to interpret the Pleistocene sequences (Figure 3). At the broad scale, the transition from marine (shelly marine sand) to aeolian provides an approxi-

Table 1. *Comparative table between seagrass assemblage molluscs—Holocene and Pleistocene.*

	Holocene Assemblage[1]	Pleistocene Assemblage
Bivalvia		
Anodontia perplexa	X	X
Brachidontes ustulatus	X	X
Callucina lacteola	X	X
Chlamys asperrimus	X	X
Chioneryx cardioides	X	X
Divalucina cumingi	X	X
Donax francisensis	X	X
Electroma georgiana	X	X
Eucrassatella sp.	X	X
Glycymeris strialularis	X	X
Gomphina undulosa	X	X
Hemidonax chapmani	X	X
Irus distans	X	X
Mactra australis	X	X
Mactra matthewi	X	X
Mysella sp.	X	X
Saccostrea cucculata	X	X
Paphies cuneata	X	X
Pinna sp.	X	X
Tawera coelata	X	X
Tawera lagopus	X	X
Tellina tenuilirata	X	X
Thraciopsis subrecta	X	X
Wallucina cf. *jacksoniensis*	X	X
Gastropoda		
Acteocina sp.	X	X
Amalda monilifera	X	X
Amblychilepas oblonga	X	X
Astralium squamiferum	X	X
Bedeva paivae	X	X
Bittium granarium	X	X
Bulla quoyii	X	X
Calyptraea calyptraeformis	X	X
Cantharidus lepidus	X	X
Cantharidus irisodontes	X	X
Cantharidus sp.	X	X
Clanculus sp.	X	X
Collisella onychitis	X	X
Cominella tasmanica	X	X
Conus anemone	X	X
Dicathais orbita	X	X
Drupa sp.	X	X
Ethminolia vitiliginea	X	X
Gibbula lehmanni	X	X
Gibbula preissana	X	X
Haminoea brevis	X	X
Hipponix conicus	X	X
Hipponix foliaceus	X	X
Leiopyrga octona	X	X
Mangelia sp.	X	X
Mitrella austrina	X	X
Mitrella menkeana	X	X
Naccula punctata	X	X
Natica sp.	X	X
Notocochlis gualteriana	X	X
Notomella bajula	X	X
Oliva australis	X	X
Parcanassa sp.	X	—
Phasianella australia	X	X
Phasianella solida	X	X
Phasianella ventricosa	X	X
Phasiatrochus bellulus	X	X
Polinices conicus	X	X
Proterato sulcerato	X	X
Pyrene scripta	X	X
Pyrenidae pseudomycla	X	X
Syrnola sp.	X	X
Thalotia conica	X	X
Thalotia lehmanni	X	X
Thalotia pulcherrima	X	X
Thalotia chlorostoma	X	X
Turbo intercostalis	X	X
Tanea sagittata	X	X
Vexillum marrowi	X	X
Zafra vercoi	X	X

[a]Identifications after GW Kendrick (Western Australian Museum) as listed in SEMENIUK and SEARLE (1985); supplementary identifications from ROBERTS and WELLS (1981) and WELLS and BRYCE (1985)

mation to sea level within 1 m, and is an interface relatively easy to locate, even if the limestones are altered. At the finer scale, the various facies within the sequence provide indication of deposition relative to sea level (SEMENIUK and JOHNSON 1982; SEARLE and WOODS 1986): (1) the interface between burrowed bank sediment and lower part of the beach sequence = c. 1-2 m below MSL; (2) laminated shelly sand within the beach sequence = c. MSL; (3) bubble sand within the beach sequence = 0.5-1.0 m above MSL; and (4) zone of *Sepia* and *Spirula* in beach sequence = 1.0-2.0 m above MSL (Table 1).

Holocene Barriers

The barriers of The Coorong, southeastern South Australia and the Leschenault Peninsula, southwestern Australia, are narrow Holocene barrier dunes extensive as linear features along the open coast for some 120 km and 60 km, respectively. The barrier of The Coorong is anchored at its extremities by bedrock (SPRIGG, 1952, 1979; SCHWEBEL, 1984), and the Leschenault Peninsula is anchored at its extremities by Pleistocene limestone. The oceanographic setting in both cases is wave-dominated, microtidal, with strong seabreezes. The importance of these systems is not so much in the stratigraphic sequence, but rather in the extensive, linear and narrow nature of the barriers. A similar narrow structure is the Chesil Bank in southern England (GOUDIE and GARDNER, 1985), though here the barrier is gravelly to the east, progressively changing to sandy to the west.

The barriers of The Coorong and the Leschenault Peninsula are of moderate relief (20-30 m), and protect long, linear, narrow lagoons, within which estuarine and lagoonal sediments accumulate. In The Coorong area, the Holocene sequence overlies and abuts older, similar linear barrier systems of Pleistocene age. In the Leschenault Peninsula, the Holocene sequence abuts a distinctly different Pleistocene system (SEMENIUK 1983). In both cases, the Holocene barrier is an assemblage of aeolian dunes composed of fine quartz and carbonate sand, and the estuarine lagoonal sediments are quartz sand, carbonate sand, terrineous mud, and carbonate mud. The barriers are retreating, retrograding locally over the estuarine lagoonal sediments.

Table 2. *Description of Pleistocene formations.*

Formation	Geometry	Description	Thickness
Kooallup Limestone	ribbon to wedge	white to cream shelly/bioturbated calcarenite, laminated cross-laminated shelly calcarenite/coquina, laminated to cross-laminated beach calcarenite, cross-laminated to structureless aeolianite; basal shelly calcilutite	5–16 m
Myalup Sand	ribbon to shoestring	mainly white quartz sand; with local lenses of calcarenite, calcilutite, and mud, all with some shell layers	5–15 m
Tims Thicket Limestone	ribbon to wedge	white to cream shelly/bioturbated calcarenite, bioturbated foraminiferal limestone, laminated cross-laminated marine calcarenite laminated to cross-laminated beach calcarenite, cross-laminated to structureless aeolianite	5–10 m
Eaton Sand	shoestring ridge	yellow and white quartz sand	20 m

Indicators for MSL in the barrier systems are as follows: (1) the interface between the estuarine lagoonal sediment and the overlying aeolian sediment where the barrier is retrograding into the leeward lagoon; and (2) the junction between shelly sand and aeolian sand on the seaward side of the barriers.

THE PLEISTOCENE LITHOFACIES

In total there are 11 suites of limestone, other sediment, and quartz sand in the Pleistocene sequences: (1) bioturbated foraminiferal calcarenite; (2) shelly/bioturbated calcarenite; (3) laminated shelly calcarenite/coquina; (4) laminated and cross-laminated marine calcarenite; (5) laminated to cross-laminated beach calcarenite; (6) cross-laminated to structureless aeolian calcarenite; (7) calcreted limestone; (8) indurated, bored limestone; (9) shelly calcilutite; (10) quartz sand; and (11) shelly mud. The sediments and limestones are described below, with interpretation as to their depositional environment based on Holocene analogues. Terminology for limestones follows DUNHAM (1962). All limestones are generally white, cream to buff in colour. Grainstones are weakly to strongly cemented by sparry calcite, depending on location relative to the water table. Most limestones also are variably weakly indurated by calcrete (GILE, *et al.*, 1966; READ, 1974) and may be stained by iron oxides. Occurrence of the lithologies within the formations is described in Tables 2 and 3.

Table 3. *Relative abundance of Marine lithofacies in the Pleistocene limestones.*[1,2]

Lithology	Lower Tims Thicket Limestone Northern Sections	Lower Tims Thicket Limestone Southern Section	Lower Kooallup Limestone Northern Sections	Lower Kooallup Limestone Central Sections	Lower Kooallup Limestone Southern Sections
Low energy facies (under seagrass cover)					
Bioturbated foraminiferal calcarenite	2	0	0	0	0
Shelly/bioturbated calcarenite	3	1	3	3	3
High energy facies (sand wave facies)					
Laminated shelly calcarenite	2	2	2	3	3
Laminated coquina	1	1	2	3	3
Laminated/cross-laminated marine calcarenite	2	1	1	1	1

[1]Upper parts of both the Tims Thicket Limestone and the Kooallup Limestone are beach and aeolian facies

[2]Relative abundance scale: 0 = absent; 1 = uncommon; 2 = present; 3 = common

Bioturbated Foraminiferal Calcarenite

Bioturbated foraminiferal calcarenite is a fine to medium sand grainstone of calcareous algae, invertebrate skeletons, quartz, shell grit, whole molluscs, and abundant granule-sized foraminifera (*Marginopora*). The sediment is bioturbated (Figures 4A, 4B), with burrows 3-4 cm diameter, penetrating vertically downwards for 50-75 cm, otherwise the bioturbation shows a general swirling of foraminiferal discs. The shell content is mainly molluscan indicative of seagrass bank community. The sediment is often found laterally equivalent to shelly/bioturbated calcarenite described below. The fossils, structures, and evidence of encrusting epibiota indicate accumulation in a shallow water, marine seagrass bank environment (SEMENIUK and SEARLE 1985).

Shelly/Bioturbated Calcarenite

Shelly/bioturbated calcarenite is fine to medium grained, bioturbated to structureless, skeletal quartz grainstone, with abundant calcareous algae and molluscs. Shell where present is randomly oriented by the bioturbation. The shell is a diverse molluscan assemblage indicative of seagrass communities and, together with the sedimentary structures and evidence of encrusting epibiota, indicates accumulation in a ma-

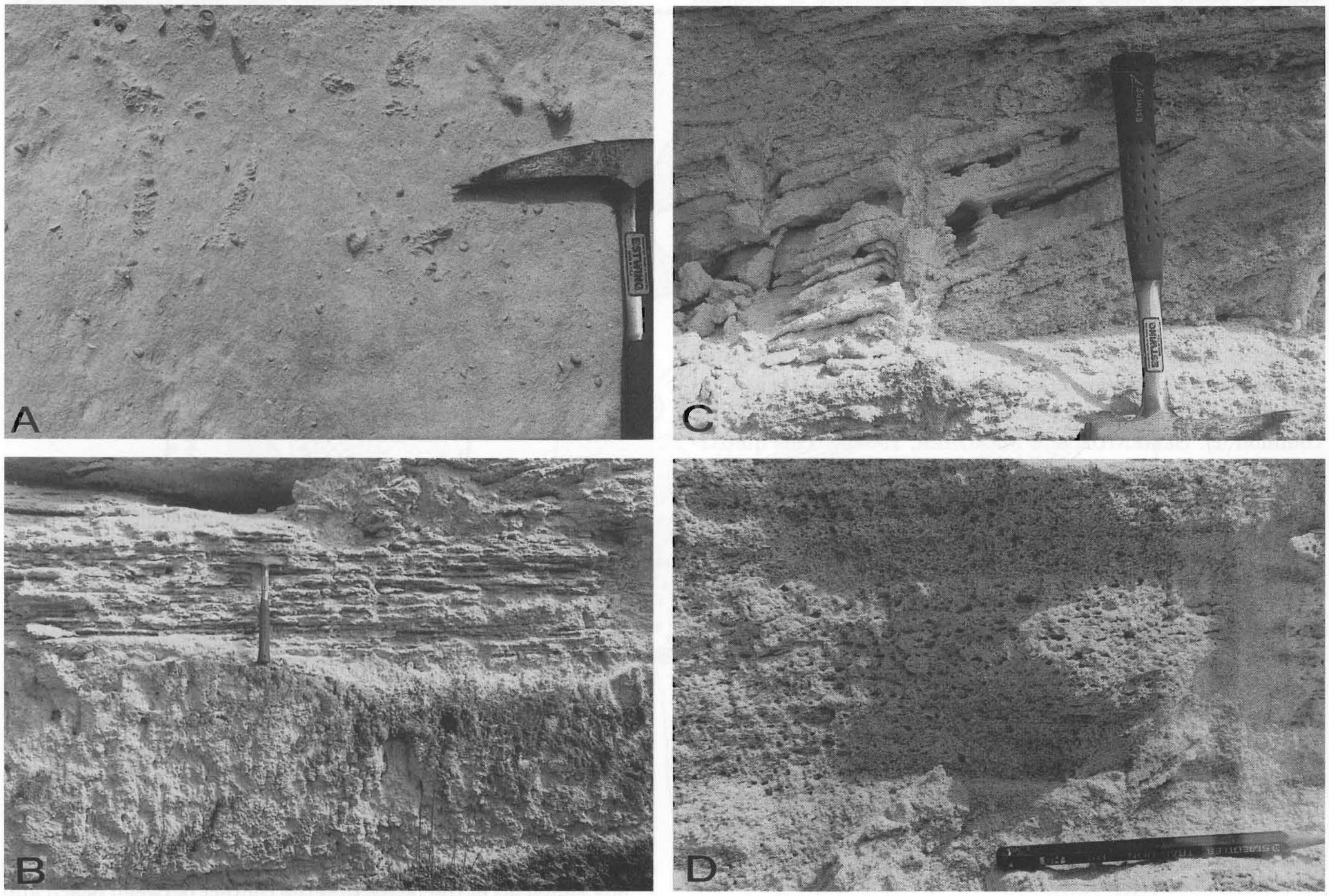


Figure 4. Field photographs of the Pleistocene limestones. (A) Vertical burrows in the bioturbated foraminiferal calcarenite of the seagrass bank facies. (B) Contact between bioturbated seagrass bank facies with vertical burrows and overlying cross bedded marine calcarenite. (C) Vertical burrows in cross bedded marine calcarenite. (D) Bubble sand structures.

rine seagrass bank environment (LOGAN *et al.,* 1970; SEMENIUK and SEARLE, 1985).

Laminated Shelly Calcarenite/Coquina

Laminated shelly calcarenite/coquina is fine, medium to coarse grained, laminated skeletal quartz grainstone, with abundant calcareous algae and molluscs, varying to shell coquina. Shell is oriented convex-up along the lamination. The shell is a diverse molluscan assemblage indicative of shallow water communities. The molluscs and sedimentary structures indicate accumulation in wave-modified seagrass bank and shoreface environments (SEMENIUK 1994).

Laminated and Cross-Laminated Marine Calcarenite

Laminated and cross-laminated marine calcarenite is medium grained skeletal quartz grainstone, generally without shell beds and is conspicuously laminated, cross-laminated and trough-bedded (Figure 4A), with local vertical burrows (Figure 4C). This limestone facies passes laterally into shelly/bioturbated calcarenite, described above. Sedimentary structures, lateral facies relationships, and its occurrence just below beach sediments indicate accumulation in a wave-agitated, shallow water marine environment. The Holocene analogue is a sand wave facies on a wave-agitated bank (SEARLE *et al.,* 1988).

Laminated to Cross-Laminated Beach Calcarenite

Limestones of this suite have variable structure and texture, but nevertheless form a vertically shoaling sequence, usually over 2.0-2.5 m, that may be described as an interrelated series. The limestones are skeletal quartz grainstone, mostly medium grained and locally coarse grained. Mollusc shell horizons are present, with shells oriented convex-up. The molluscan assemblage is limited—*Donax* is the most common, but *Glycymeris, Donacilla* and gastropods also occur. Sedimentary structures and two diagnostic cephalopod species distinguish the various subfacies in this suite (Figure 3; SEMENIUK and JOHNSON 1982). The lower part is trough-bedded, medium to coarse grained, with local shell beds; today, such sediment accumulates in shallow subtidal beaches. The middle zone is medium to coarse grained, with oriented shell horizons and low inclined cross-lamination; it represents a beach swash zone. The next subfacies is medium grained, with bubble-sand structures (Figure 4D), and today forms in the upper tidal beach. The uppermost subfacies is crudely layered to bioturbated to structureless, medium to coarse grained, and has the diagnostic "floatable" cephalopod skeletons *Sepia* and *Spirula* and bioturbation structures due to the ghost crab *Ocypode*; this sediment accumulates today at storm water levels on beaches.

Cross-Laminated to Structureless Aeolian Calcarenite

Cross-laminated to structureless aeolian calcarenite is fine to medium grained skeletal quartz grainstone. Cross-lamination is large scale with sets 2-5 m high. Cross-laminated aeolian calcarenite passes laterally into structureless aeolian calcarenite. Calcrete rhizoconcretions and calcreted pipes are common (*cf.* SEMENIUK and MEAGHER, 1981b). This quartzose limestone, with its grainsize, sedimentary structures, calcrete rhizoconcretions, and overall geometry has its analogue in Holocene coastal dunes.

Calcreted Limestone

This is a limestone composed mainly of calcrete, *i.e.,* cryptocrystalline low-Mg calcite (GILE *et al.,* 1966; READ 1974). The calcrete is sheet-like, 20-30 cm thick, or massive, within and on top of the parent limestone, or forms coatings to pipes. Lateral and vertical relationships and gradations and palimpsest grains and textures indicate parent lithology to be aeolianite, but for the most part calcrete is now dominant. Such limestone is best developed at unconformity surfaces, and indicates a major subaerial exposure.

Indurated, Bored Limestone

This limestone is variable from aeolianite to shelly limestone and may also be calcreted. Its distinguishing feature is induration by calcite cements (fine grained calcite, sparry calcite, calcrete), borings and pot-holes. Borings are 1 cm diameter or less. The surface of the limestone may show sediment-filled fissures and local pot-holes some 10-30 cm diameter. The pot-holes, fissures, and limestone surface may be veneered with rounded limestone gravel and shells of *Ninella, Marmarstoma, Littorina,* limpets and barnacles. This limestone type and its gravel and fauna have analogues in Holocene rocky shore platforms in this region (SEMENIUK and JOHNSON 1985).

Shelly Calcilutite

Shelly calcilutite is lime mudstone to skeletal lime mudstone. It is structureless except for shell beds. Similar sediment forms in deep water basins adjoining seagrass banks (SEMENIUK and SEARLE, 1987b).

Quartz Sand

Quartz sand is yellow, white or grey. It is medium grained, well to poorly sorted, and composed mostly of quartz with some feldspar and minor heavy minerals (GLASSFORD and SEMENIUK, 1990). The quartz sand facies of this study is largely structureless, but elsewhere it exhibits large scale aeolian cross bedding (SEMENIUK and GLASSFORD, 1990). The sand is Pleistocene and has no Holocene analogue on the Swan Coastal Plain. Similar thick, ridge-forming deposits of yellow sand were interpreted by SEMENIUK and GLASSFORD, (1988) to be mainly continental aeolian. Where such quartz sand is intimately related stratigraphically and geomorphically with marine deposits (as in this area), it tends to be white or grey and is likely to be a locally reworked shore deposit.

Shelly Mud

Shelly mud is dark grey, structureless terrigenous mud with estuarine shells. The lithology and shell content is similar to sediment accumulating today in estuarine lagoonal settings (SEMENIUK, 1983).

Sea Level Indicators in the Limestone

Facies and structures in the limestones which are useful for determining the relative position of former sea levels were applied at two scales. The general junction between shelly limestone and aeolian fine sand can be used to locate MSL at a gross scale, particularly where limestones have been altered by calcrete, vugular porosity and pedogenesis and cores did not exhibit enough lithological/structural detail to precisely fix the position of former sea levels. The shell components and fine sand nature of the lithology are two attributes relatively easy to determine, and the position of the Pleistocene MSL determined by this method can be fixed to within 1 m. At a finer scale, where limestones exhibited well preserved small scale facies, it was possible to resolve the various subfacies of the beach and the contact between beach and seagrass facies and hence determine the relative position of former sea levels to within 0.5 m. Limestones with a well preserved sequence of facies useful for determining the Pleistocene MSL were evident in many cores, road cuts and quarries.

THE PLEISTOCENE SYSTEM WITHIN THE YALGORUP PLAIN AND THE ADJOINING UNITS

The Yalgorup Plain is a long, narrow plain, some 60 km long and 5-6 km wide. Though generally of low relief and undulating, there is local relief of 5-10(–15) m in the form of aeolian limestone ridges or quartz sand ridges. The Plain is bordered to the east by an ancestral hinterland ridge (the Mandurah-Eaton Ridge) that is a linear, moderately high system, 20 m high and 3-4 km wide, extending in a north–south direction for 90 km from Mandurah to Eaton (Figure 5), with a slight concavity in its form on the western margin. The junction of the ridge with the Yalgorup Plain is sharp with the ridge descending steeply down to the Plain. The Mandurah-Eaton ridge is composed of Pleistocene aeolian yellow quartz sand and aeolian limestone but has variable stratigraphy: to the south, it is mainly quartz sand and lesser limestone, with limestone occurring as aeolianite lenses (SEMENIUK and GLASSFORD, 1988); to the north, limestone is more common. Even where limestone dominates, the ridge is mantled by yellow quartz sand. Stratigraphically, the sediment

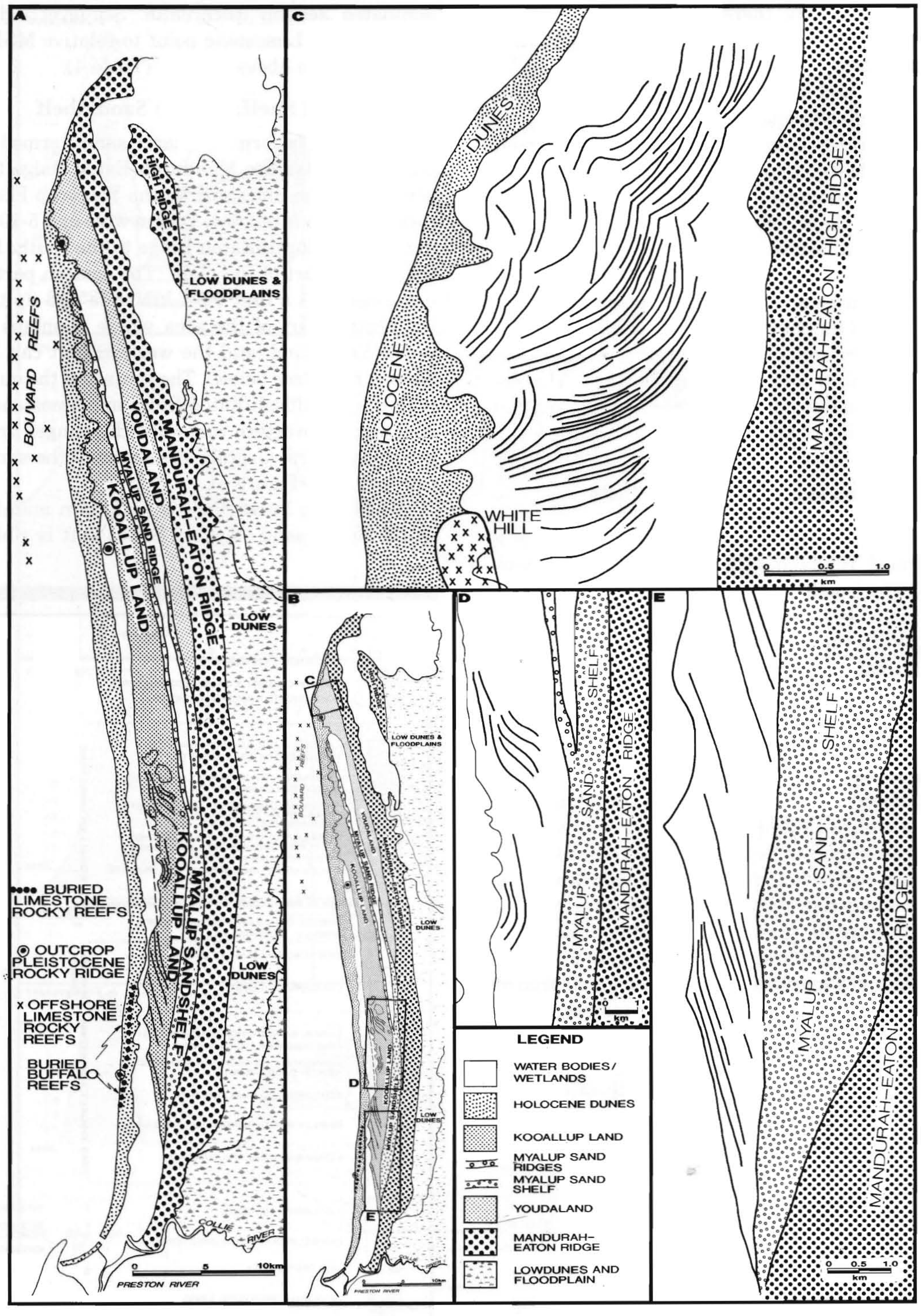


Figure 5. Map of the Pleistocene geomorphic units (landforms) on the Yalgorup Plain, and detail of beachridge trends in selected areas.

under the Mandurah-Eaton Ridge is underlain by shelly limestone that extends to the offshore limestone ridges, indicating that the Mandurah-Eaton Ridge is younger than the limestone of the offshore ridges.

A discontinuous system of ridges and knolls of Pleistocene aeolian limestone occurs in a north-south linear trend immediately to the west of the Yalgorup Plain (Figure 5). One ridge system forms offshore rocky reefs in the Bouvard Reefs area to the north. Another occurs buried under Holocene dunes to the south. Generally, there are no prominent limestone ridges or rocky reefs, buried or otherwise, in the central part of the area.

The Yalgorup Plain and adjoining areas are described below in terms of the Pleistocene components as follows: (1) older limestone beachridge plain (Youdaland); (2) quartz sand shelf (Myalup Sand Shelf); (3) quartz sand barrier ridge (Myalup Sand Ridge); (4) younger limestone beachridge plain (Kooallupland); (5) northern offshore limestone ridge (Bouvard Reefs); and (6) southern limestone ridge (Buffalo Reefs). The disposition of these is shown in Figure 5. Their stratigraphy is shown in Figures 6 & 7. Each of these units is described below as to its landform expression within the Yalgorup Plain, its eastern and western margins, stratigraphy and contact relationships, and other key features. The description of the Pleistocene landforms and stratigraphy is provided without the Holocene cover.

Youdaland: Older Limestone Beachridge Plain

The oldest limestone unit on the Yalgorup Plain forms a narrow strip, termed Youdaland, in the central to northern part of the area. The Youdaland is an undulating, low relative relief (6 m) plain, up to 3-4 km wide, that extends north-south for 40 km. While the overall shape of the unit is ribbon-like, to the north it has the shape of a cuspate foreland within which former beachridges, preserved now as low-relief calcrete-indurated calcarenite ridges, are evident on the surface. The cuspate pattern of the former beachridge trends and the complex cuspate accretion also are evident (Figure 5).

Youdaland is underlain by the Tims Thicket Limestone. This formation is ribbon-shaped. It unconformably overlies older Quaternary sediments at depth, pinches out unconformably eastwards against sediments of the Mandurah-Eaton Ridge, and pinches out down-dip (westwards) as a natural synoptic surface (Figure 6). It is unconformably overlain by the Myalup Sand filling a karst surface cut into the limestone. In the vicinity of Cape Bouvard, there is an outcrop of a former island (White Hill, Figure 5C) that has been "captured" within the former beachridge plain; but for the most part, the offshore limestone ridge system that promoted the formation of this cuspate foreland exists presently offshore as the Bouvard Reefs.

Within the limestone under Youdaland, five types of facies are present; in stratigraphic order these are, from top to base: (5) cross-laminated to structureless aeolian calcarenite; (4) laminated to cross laminated beach calcarenite; (3) laminated and cross laminated marine calcarenite; (2) bioturbated foraminiferal calcarenite; and (1) shelly/bioturbated calcarenite with seagrass assemblage biota.

The limestone types are in sequence of shoaling, with seagrass bank lithofacies and the laterally equivalent sand wave lithofacies passing up into the beach sequence and then into the beachridge/dune sequence (Figures 6 and 7). Within the beach facies, the subfacies are also in a shoaling sequence: trough cross-bedded calcarenite passes up into laminated calcarenite with *Donax* (a beach zone indicator), into calcarenite with bubble structures, into structureless calcarenite with *Sepia* and *Spirula,* and then finally into large scale cross-laminated aeolian calcarenite. Sea-level indicators in the Tims Thicket Limestone point to relative MSL during deposition as 3.0 m above present (Table 4).

Myalup Sand Shelf: Quartz Sand Shelf

A narrow platform of quartz sand, termed Myalup Sand Shelf, separates the Mandurah-Eaton Ridge from the younger Pleistocene limestone on the Yalgorup Plain. The quartz sand platform is narrow, 1-2 km wide and 5-10 m high, flanking the Mandurah-Eaton Ridge to the south. It bifurcates in the central part of the plain. The eastern part can be traced northwards as a unit 0.5-1 km wide and up to 5 m high, to the central part of the area where it onlaps the limestone under Youdaland, and the western part can be traced as a narrow ridge (see below). The contact of the quartz sand body with the Mandurah-Eaton Ridge and limestone of Youdaland is sharp; the western contact with younger limestone also is generally sharp. Overall, the shape of the sand body is narrow and long (Figure 5).

The Myalup Sand Shelf is underlain mainly by grey and white quartz sand (Myalup Sand) that is ribbon-like (up to

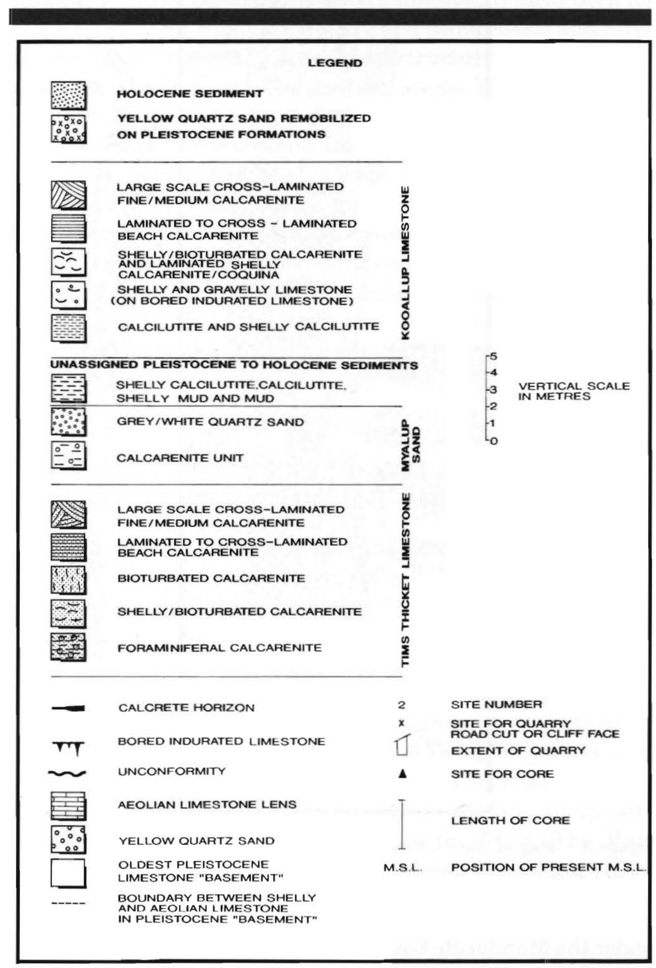


Figure 6. Stratigraphic sections, Transects 1–9. Location of profile and sections shown in Figure 1. Transect 8 is shown in Figure 7. →

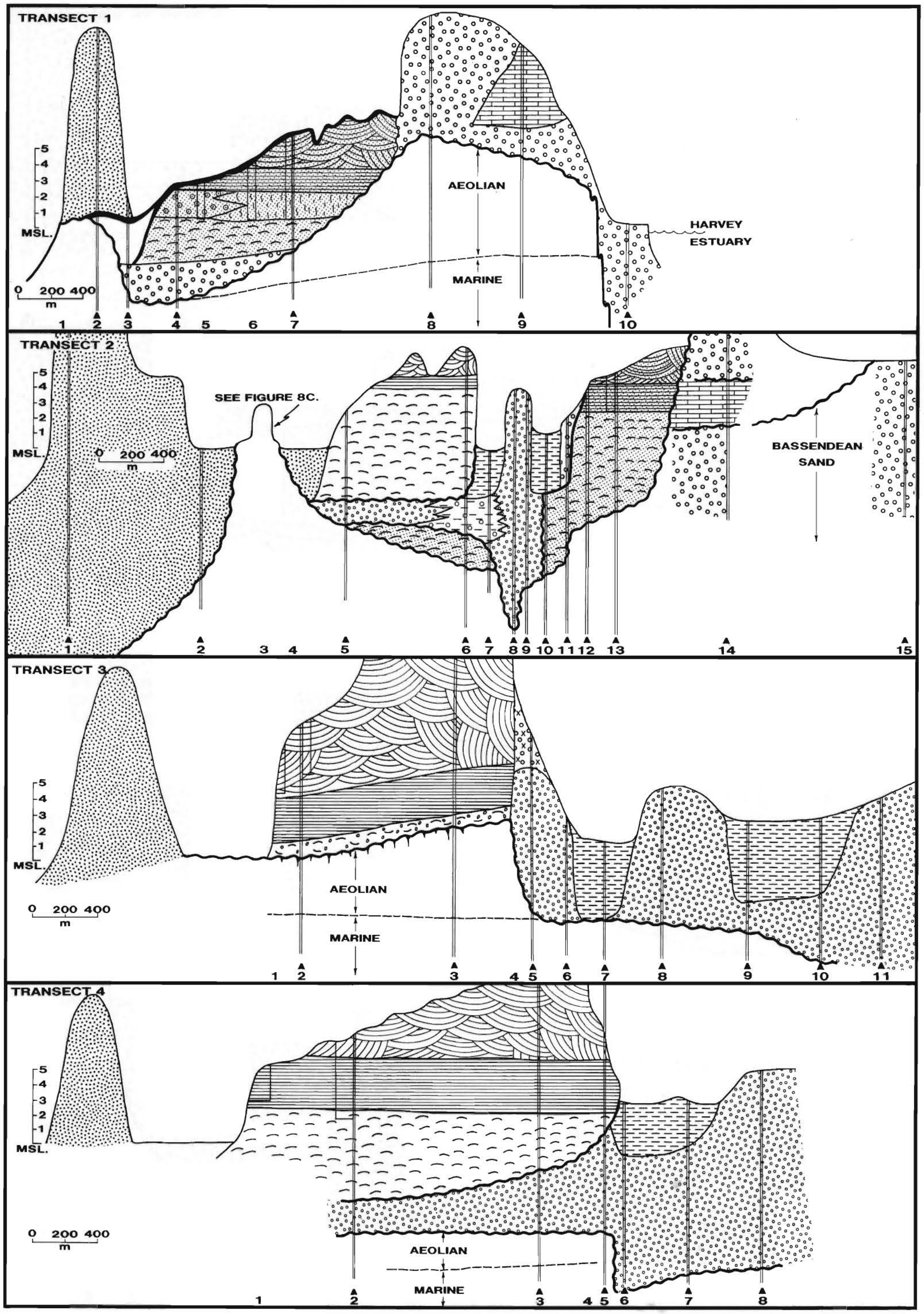
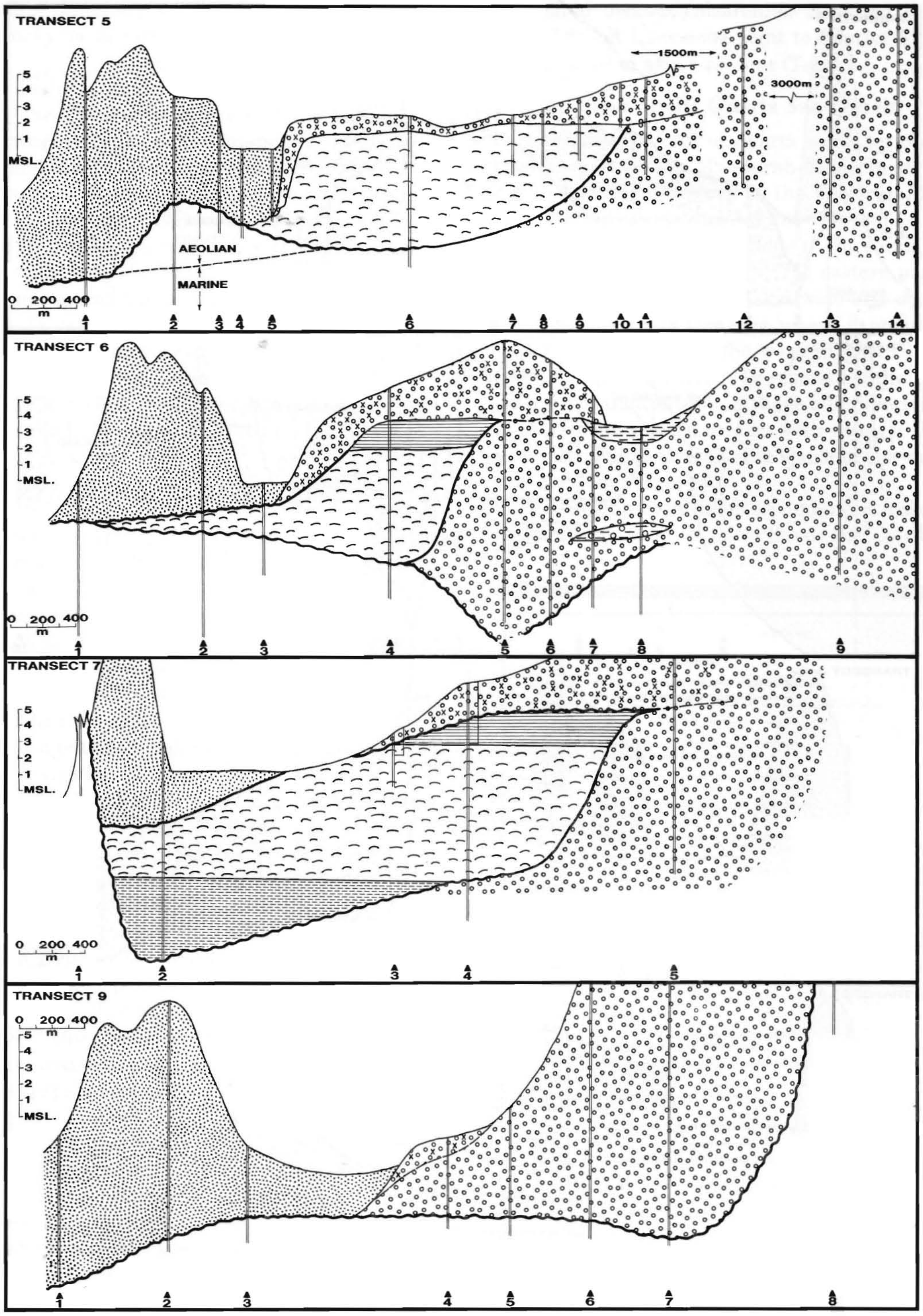


Figure 6. Continued. →



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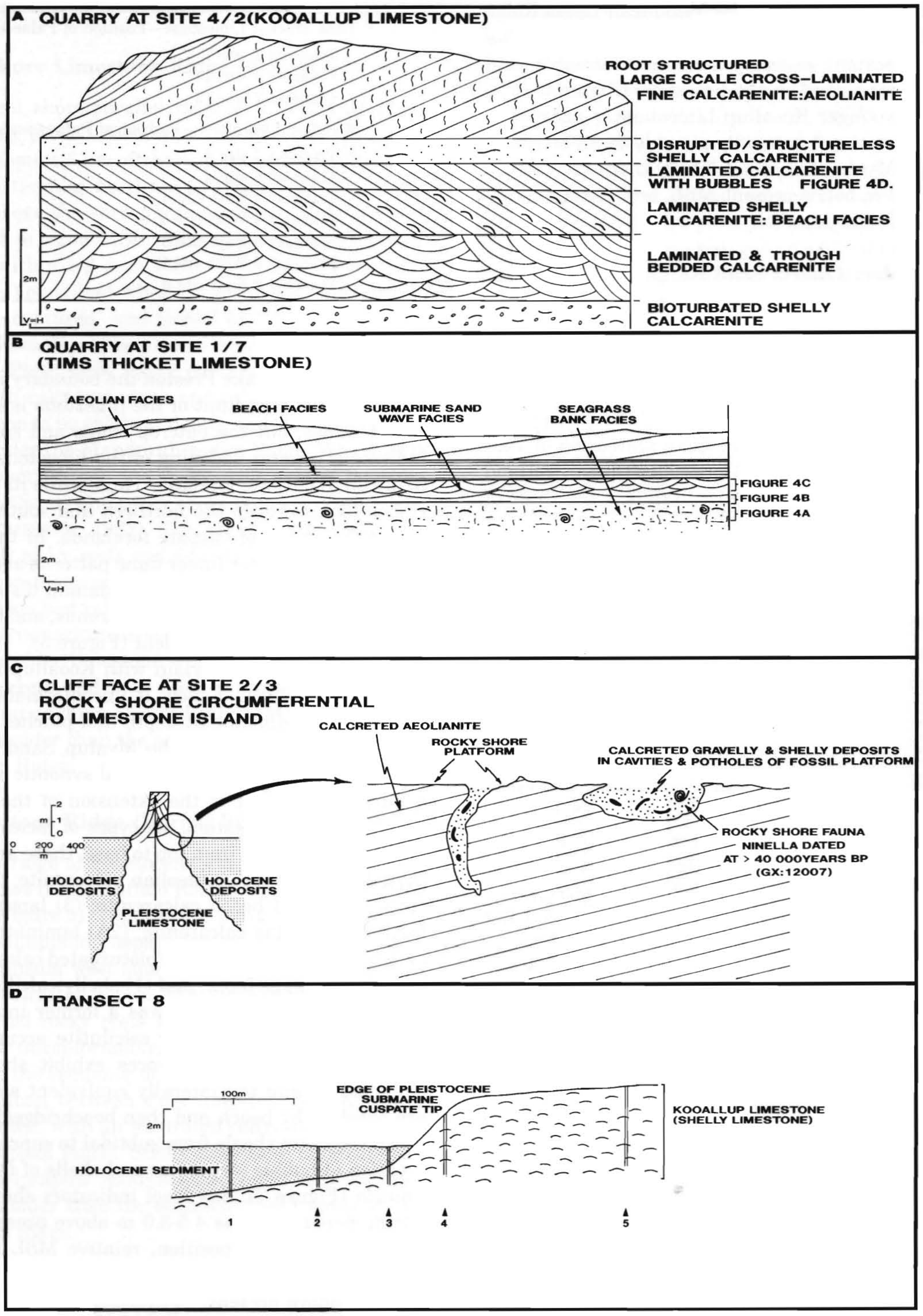

Figure 7. Detailed stratigraphy drawn from quarry facies of some of the facies in the Pleistocene limestone. (A) Beach to beachridge sequence (Transect 4, Site 2). (B) Seagrass facies, marine sand-wave facies, and beach to beachridge facies (Transect 1, Site 4). (D) Rocky shore (Transect 2, Site 3). (E) Synoptic surface of the seaward edge of the cuspate seagrass bank along Transect 8.

10 m thick, 2000 m wide, and 40 km long). The stratigraphic contact of the Myalup Sand with the Mandurah-Eaton Ridge is difficult to differentiate. The contact with the underlying Tims Thicket Limestone is sharp and unconformable, and marked by prominent karst in the limestone (Figure 6). The contact with the younger Kooallup Limestone is sharp and unconformable. It was not generally possible to differentiate facies within the Myalup Sand, but locally there are carbonate-rich layers 2-3 m below present MSL, and these may indicate former shoreline deposits.

Myalup Sand Ridge: Quartz Sand Ridge

A narrow low ridge of quartz sand, termed the Myalup Sand Ridge, separates the younger Pleistocene limestone on the Yalgorup Plain from the older Tims Thicket limestone. The ridge is some 500 m wide and 4-5 m high and continues as a narrow, straight sand ridge virtually to the north of the area until it is terminated by the cuspate protrusion of Youdaland. The ridge separates two depressions (linear wetland chains). The eastern margin of the ridge thus is the shore of a wetland. The western contact of the ridge with the younger limestone is sharp, but to the north, it is modified locally by reworking along wetland/lake margins. Overall, the shape of the sand body is narrow, long and straight (Figure 5).

The Myalup Sand Ridge is underlain by a shoe-string body of grey and white quartz sand (Myalup Sand), up to 10 m thick, 500 m wide and 40 km long, flanked by a variety of sediments that fill the linear depressions that border it. As described above, it was not possible generally to differentiate facies within the Myalup Sand, but locally there are thin carbonate-rich layers; these are generally 2-3 m below present MSL and may indicate the relative level of the Pleistocene sea at time of deposition. In the depressions adjoining the ridge, there is a variable suite of facies that overlie quartz sand: calcilutite, shelly calcilutite, and shelly terrigenous mud (Figure 6). The stratigraphic contact of the Myalup Sand of the Myalup Sand Ridge with the younger Kooallup Limestone is sharp and unconformable, with the base of the limestone truncating the ridge-and-depression sequence within the Myalup Sand, and the Myalup Sand underlying but pinching out under the Kooallup Limestone.

Kooallupland: Younger Limestone Beachridge Plain

The youngest limestone on the Yalgorup Plain crops out in a narrow strip, termed Kooallupland, in the southern to central part of the area. Kooallupland is a generally undulating plain of low relative relief (6 m), with local prominent former dune ridges up to 15 m high. It is generally 2-3 km wide and extends north-south for 60 km. The terrain is bounded along its entire eastern length by a sharp, straight contact with Myalup Sand. The western margin of the landform usually is marked by onlapping Holocene dune or estuarine-lagoon deposits; in general, however, the limestone persists in subcrop beneath the Holocene formations. Where exposed, the western margin of the limestone terrain is one of three types: (1) to the south it has natural geomorphic cuspate shapes; (2) the central part has a straight margin, with natural synoptic relief preserved; and (3) in local areas where it forms the eastern shore of Lake Preston the boundary is eroded. To the north, the western limit of the limestone is obscured by Holocene dunes, but the outcrop shape and subcrop extension indicate a general widening of the limestone here to form a (truncated) cuspate foreland. Thus, while its overall shape is ribbon-like, towards the northern and southern extremities it has the shape of cuspate forelands. In the southern and central parts, former linear dune patterns are evident as surface features, and as for the Youdaland history, the cuspate pattern of the former beachridge trends, and the complex cuspate accretion also are evident (Figure 5).

Table 4. *Height of Palaeo-sealevel indicators in Pleistocene limestones.*

Tims Thicket Limestone—Position of Palaeo-sealevel	
Transect 1 site 7	3.0 m
Transect 2 site 14	3.0 m
Transect 2 site 13	3.0 m
Kooallup Limestone—Position of Palaeo-sealevel	
Transect 7 site 4	4.0 m
Transect 6 site 4	4.0 m
Transect 4 East site 4	4.5 m
Transect 4 West site 2	4.5 m
Transect 3 East site 3	4.0 m
Transect 3 West site 2	3.0 m
Transect 2 East site 6	4.0 m

Kooallupland is underlain with Kooallup Limestone. This formation is ribbon-shaped. It unconformably overlies older Quaternary sediments at depth and pinches out unconformably to the east against the Myalup Sand; to the west, it pinches out down-dip as a natural synoptic surface, or abuts a buried ridge that is the extension of the Bouvard Reefs system. In the formation, six types of facies are present. In stratigraphic order, from top to base, these are: (5) cross-laminated to structureless aeolian calcarenite; (4) laminated to cross laminated beach calcarenite; (3) laminated and cross laminated marine calcarenite; (2A) laminated shelly calcarenite/coquina; or (2B) shelly/bioturbated calcarenite with seagrass assemblage biota; and (1) shelly calcilutite.

Along Transect 2, there was a former inter-ridge marine depression and deep water calcilutite accumulated. In the main, the limestone sequences exhibit shoaling; seagrass bank facies, and the laterally equivalent sand wave facies, are overlain by beach and then beachridge/dune facies. The beach sequence shoals from subtidal to supratidal, with preservation of bubble structures and shells of *Donax, Sepia* and *Spirula* (Figure 7). Sea level indicators show relative MSL during deposition was 4.5-3.0 m above present (Table 4): at the beginning of deposition, relative MSL stood 4.5-4.0 m above present, but during progradation it fell progressively to 3.0 m above present.

An additional feature within the Kooallup Limestone is a south to north facies change; to the south, beachridge and dune facies above the seagrass bank and beach facies are quartz sand rich; to the north, the sediments are more carbonate-grain rich. This transition is related to major input of quartz sand from two sources in the south: erosion of the Mandurah-Eaton Ridge (with concomitant net northwards longshore drift), and the Collie, Preston and Brunswick rivers which transport quartz from the dunes east of the Mandurah-Eaton Ridge.

Northern Offshore Limestone Ridge (Bouvard Reefs)

There is a local shore-parallel ridge of Pleistocene limestone, now largely eroded, forming a line of rocky reefs (the Bouvard Reefs) some 4-5 km offshore, commencing in the central area and extending northwards (Figure 5). The reefs stand 10-20 m above the surrounding seafloor, and their top generally is c. 4-5 m below MSL, although local pinnacles and reefs extend to within 1-2 m of MSL. The reefs are best developed opposite Youdaland where it is cuspate. Portions of this system are "captured" and buried by the Tims Thicket Limestone and Kooallup Limestone. Outcrops of these reefs on the Yalgorup Plain show upper parts of the limestone to be aeolianite with calcreted pipes and calcrete sheets; cores show the limestone to be shelly at depth, and this shelly limestone extends under the Mandurah-Eaton Ridge. Where well exposed, the former islands and rocky reefs exhibit features such as shore platforms and rocky shore fauna (Figure 7; SEMENIUK and JOHNSON, 1985). The stratigraphic relationships of the fossil rocky reefs and islands with Tims Thicket and Kooallup limestones are discordant and/or unconformable. Where the reefs had relief, the older rocky reef limestone rises abruptly, terminating the sequence of the younger limestone; where the older limestone was planed, the contact is indurated by calcrete and may have a hard-bottom fauna. Stratigraphic relationships also indicate that the limestone of these ridges is older than the sediment that comprises the Mandurah-Eaton Ridge.

Southern Limestone Ridge (Buried Buffalo Reefs)

A north–south ridge of Pleistocene limestone is buried under Holocene dunes in the Buffalo Road area, north Leschenault Peninsula (Figure 5). This ridge is located west to southwest of the Kooallupland cuspate foreland. Outcrop on the Leschenault Peninsula west shore shows a calcreted aeolian limestone with calcreted pipes. The stratigraphic relationships of the buried rocky reefs with Kooallup Limestone is discordant and/or unconformable; the rocky reefs rise abruptly and terminate the sequence of the younger limestone (Figure 6), or the contact between older limestone and Kooallup Limestone is planed, with an indurated calcreted surface, often with hard-bottom fauna. Shelly limestone underlies the ridges, and stratigraphic relationships again indicate that this limestone is older than the sediment that comprises the Mandurah-Eaton Ridge.

INTERPRETATION OF THE PLEISTOCENE SYSTEM

The overall history of the Yalgorup Plain records sedimentation and progradation in a coastal setting, changes in sedimentation style from cuspate foreland and shoreface accretion to barrier formation, and alternation in sedimentation from carbonate-rich to quartz-rich.

As described earlier, the various types of Pleistocene geomorphology in this area have modern analogues in coastal and marine environments in terms of plan shape and surface morphology. Thus, cuspate margins to parts of the Yalgorup Plain have counterparts in the modern shoreline, and prominent dune-lines on the Pleistocene plain also have counterparts in the higher-than-normal dune lines on Holocene beachridge plains (SEARLE *et al.*, 1988). Holocene cuspate shores, through accretion, develop the distinctive complex internal features of beachridge plains, and the surface morphology of parts of Youdaland and Kooallupland exhibit this type of beachridge complexity. The linear ridge of quartz sand (Myalup Sand Ridge) has geomorphic analogues in the Holocene, in open coastal settings, such as at The Coorong and the Leschenault Peninsula.

The various stratigraphic sequences in the Pleistocene units also have analogues in Holocene coastal and marine environments in terms of specific facies and biota, as well as sequences of facies. Thus, the Pleistocene lithologic sequences have their counterpart in Holocene stratigraphic sections under prograded sandy plains, recording sedimentary shoaling from subtidal seagrass facies and sand wave facies to beach, beachridge and dune facies.

Each of the Pleistocene limestone and quartz sand formations accumulated at a separate still-stand of sea level, and are separated by prominent subaerial unconformities. The evidence for this is as follows: (1) a major karst surface separates the Tims Thicket and Myalup formations; (2) soils and major stratigraphic truncation occur between Kooallup and Myalup formations; and (3) each formation has its own internally consistent sea level history. Unconformities on carbonate formations are strongly calcreted; those on quartz sand formations truncate the underlying stratigraphic sequences. Thus, the sequence from Tims Thicket Limestone to Kooallup Limestone does not represent stages of coastal progradation within the one interglacial stillstand, but rather, three separate marine transgressions within the Pleistocene.

The progressive accretion from Youdaland to Kooallupland thus records, with subaerial interruptions, various phases in the Pleistocene when carbonate production was marked and coastal carbonate sediments were dominant, and when carbonate production was minimal and coastal quartz sand was dominant, and records coastal sedimentation in cuspate forelands and prograded shorefaces, and sedimentation in coastal barriers. These phases of carbonate production and sedimentation were as follows (Figures 8 and 9): (1) Youdaland Stage: marked carbonate production; progradation of the shoreface and cuspate forelands; (2) Myalup Sand Stage: minimal carbonate production; construction of sand coastal platform and barrier; and (3) Kooallupland Stage: marked carbonate production; progradation of the shoreface and cuspate forelands.

It appears that progradation was most marked in this area under two conditions: where carbonate production was extant (so that sufficient sediment was generated to promote progradation) and where there was shelter from open oceanic conditions (*i.e.*, leeward of rocky reefs). When carbonate production was low, quartz sand from southern parts of the hinterland ridge was reworked by coastal processes and mobilised northwards to develop shore-fringing sand platforms and sandy barriers, but during this phase there was no pronounced coastal accretion and progradation.

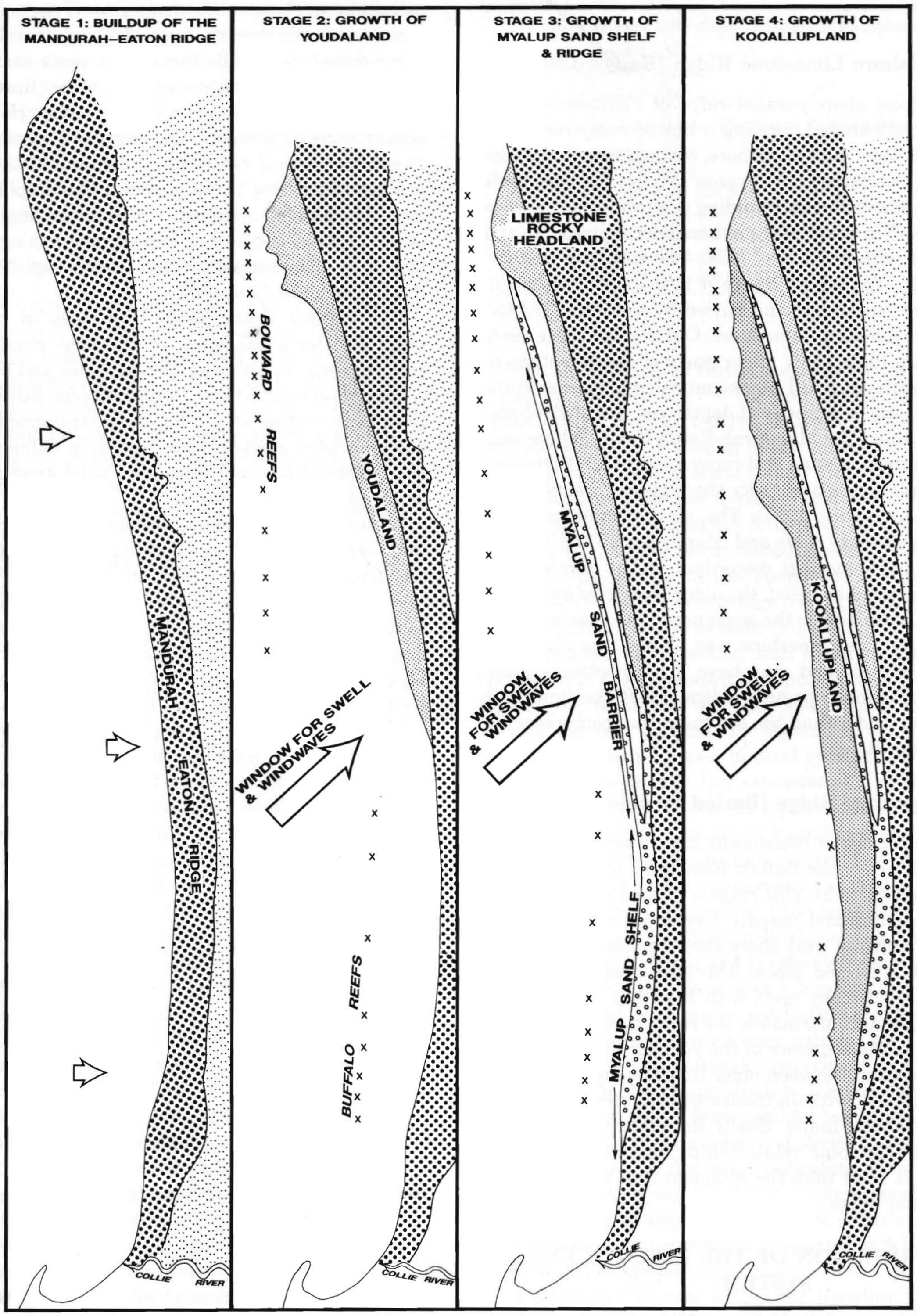

Figure 8. Reconstructed palaeogeography during Pleistocene time. Stage 1: Building of the Mandurah-Eaton Ridge. Stage 2: During Youdaland time. Stage 3: During Myalup Sand Shelf and Myalup Sand Ridge time. Stage 4: Kooallupland time.

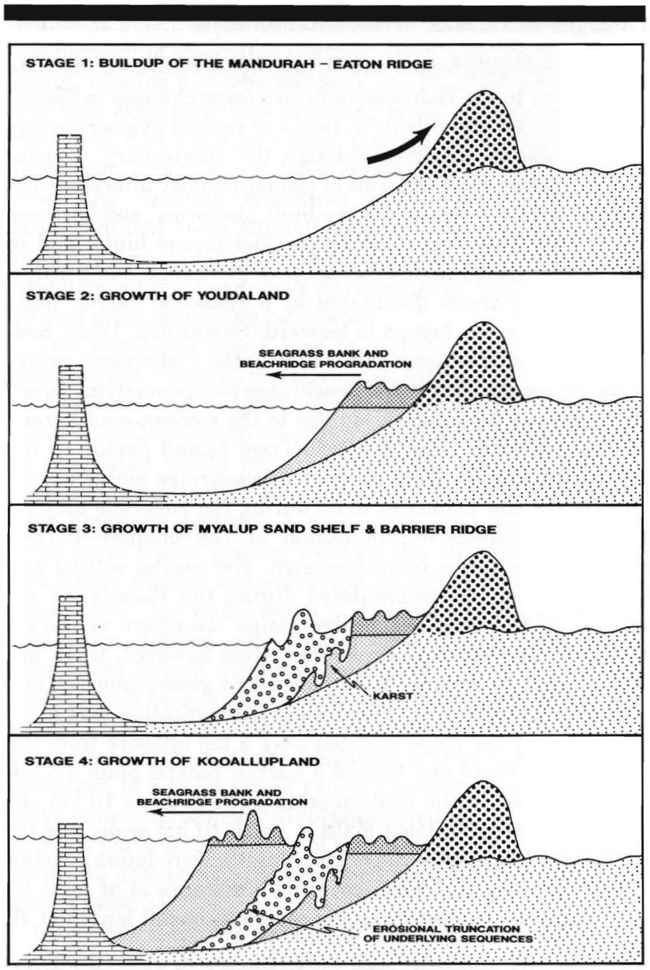

Figure 9. Reconstructed geological history Pleistocene time, showing stratigraphic stages in the progressive building of the Yalgorup Plain.

The distribution of the older Pleistocene limestone that forms the offshore rocky reef trends indicates that there is a gap between the Bouvard Reef trend and the Buffalo Reef trend. Based on modern oceanographic patterns of south-westerly swell and wind-wave driven coastal processes, this gap would have been a site where a straight coast would have developed, for two reasons: firstly, there are no offshore islands/reefs to promote cuspate foreland coastal forms; and secondly, uninterrupted swell and wind-wave trains would have straightened the coast. Thus, the straight portions of Youdaland, the Myalup Sand Shelf, the Myalup Sand Ridge, and Kooallupland correspond to those sections of coast that would have received swell and wind-waves through the reef gap.

The reconstruction of the Pleistocene history in this study is presented as follows: Stage 1—coastal erosion of quartz sand hinterland; Stage 2—shoreface, cuspate foreland sedimentation—Youdaland; Stage 3—coastal sand formation—Myalup Sand Shelf and Ridge; Stage 4—shoreface, cuspate foreland sedimentation—Kooallupland; Stage 5—post-depositional, geomorphic modifications.

Because of their variability in cementation and original relief and hence variability in erosion rates, spatially and temporally, it has not been possible to reconstruct the detailed local effects of the offshore islands and reefs on the coastal plain sedimentation into a palaeo-geographic synthesis.

The first stage of coastal history involved the truncation and bulldozing of a low-relief plain of aeolian quartz sand (SEMENIUK and GLASSFORD 1988) by a marine transgression into a prominent coastal ridge to form the Mandurah-Eaton Ridge. This ridge was then to form the hinterland for all later events and was to be one of the sources of quartz sand for later coastal sedimentation. The various later phases of coastal carbonate sedimentation in this region would have mobilised isolated carbonate-rich coastal dunes onto the ridge and developed additional limestone lenses within the quartz sand body (SEMENIUK and GLASSFORD, 1988). Thus the ridge, initially formed as a quartz-rich coastal ridge, would have accreted additional lenses of carbonate sand to develop into the final quartz-sand-and-limestone-lens body that it is today. The Mandurah-Eaton Ridge is curved, with a concavity on its western margin; it is within this concavity that all subsequent sedimentation has been localised. A reconstruction of palaeogeography at this time is shown in Stage 1 of Figures 8 and 9.

The next stage of coastal sedimentation in this area involved accumulation of the Tims Thicket Limestone to form Youdaland. The system, on the basis of geometry, surface morphology, stratigraphy and modern analogues is interpreted to be a seagrass bank deposit capped by beachridges. Two types of landform had developed. Leeward of the Bouvard Reefs, the terrain was a cuspate foreland, with internal complex structures of beachridges (Figure 5). Where the offshore ridges were less prominent, or absent, the terrain was a shore-fringing sand shelf. In both situations, the sequence of facies indicates that progradation was effected by sedimentation and accretion under seagrass bank conditions and shoaling to beach and beachridge environments. Complexities in the beachridge terrain (Figure 5C) indicates the presence of nearby islands and rocky reefs. A reconstruction of the palaeogeography at this time is shown as Stage 2 in Figures 8 and 9.

Following development of Youdaland, there was a major period of subaerial exposure, with weathering, calcretization and karst development. The next stage of coastal history involved construction of the Myalup Sand Shelf, as a deposit reworked from the still exposed southern part of the Mandurah-Eaton Ridge. This deposit was shore-fringing and essentially a wave-built platform and coastal aeolian structure. The sand was mobilised for a limited distance northwards to onlap the northern Youdaland shore. Later, perhaps due to a slight fall in relative MSL, or to a change in regional wind patterns and hence wind-wave patterns, a sand body split from the main Myalup Sand Shelf to develop a barrier, anchored to the north by the limestone headland of the Youdaland cuspate foreland and to the south by the exposed part of the Mandurah-Eaton Ridge. It may have developed initially from an alongshore spit anchored to the Mandurah-Eaton Ridge. Inter-ridge lagoons in this barrier setting were filled with wetland and lagoonal sediments, and the stratigraphic system that developed consisted of a sand-ridge-and-basin-filled suite. The stratigraphic relationships within the Myalup Sand show that the barrier did not retrograde over its associated basin-fill sediments, indicating that as a coastal structure it was essentially static. Reconstruction of palaeogeography at this time is shown as Stage 3 in Figures 8 and 9.

Another period of subaerial exposure followed, and with the return of the next marine transgression, the Myalup Sand was eroded and truncated by coastal processes. The final stage of Pleistocene coastal sedimentation in this area then involved a return to carbonate production and accumulation of the Kooallup Limestone to form Kooallupland. The system, similar to that in Youdaland, is interpreted to be a seagrass bank deposit capped by beachridges. Again, two types of landform developed. To the north and south, leeward of the Bouvard Reefs and Buffalo Reefs, respectively, the terrain remained a cuspate foreland, with internal complex structures of beachridges (Figure 5D,E). In central parts, where the offshore ridge was less prominent, or absent, the terrain developed into a shore-fringing sand shelf. However, in the central area, it is also clear, from the complex internal patterns of beachridges, that earlier in the history of the plain, there were local effects due to nearby islands: such islands, or rocky reefs, would have developed complex cuspate coastal forms along the mainland, but later with marine degradation of these islands and reefs, the coast would have been more exposed and would have developed a straight coastal form. As for the evolution of Youdaland, in both situations of cuspate foreland and shore-fringing sand shelf, progradation was effected by sedimentation and accretion under seagrass bank conditions and shoaling to beach and beachridge environments. A reconstruction of palaeogeography at this time is shown as Stage 4 in Figures 8 and 9.

Subsequent to Stage 5, there was another relative sea level fall, and the terrain of Kooallupland was subject to weathering, erosion, calcretization and karstification. The current Holocene incursion has resulted in estuarine-lagoonal and barrier dune deposits that partly bury the terrain of Youdaland and Kooallupland where they extend prominently to the west. In addition, throughout the late Pleistocene and during the Holocene, the whole Yalgorup Plain underwent groundwater and fluvial modification to develop wetlands as fluvial, lacustrine and karst geomorphic overprints on the systems. Wetland development has been most pronounced along the unconformity boundaries between the various Pleistocene landform units. However, this is the subject of another study (C.A. SEMENIUK and SEMENIUK 1995).

DISCUSSION & CONCLUSIONS

The results of this study provide several insights into the Quaternary history of the Swan Coastal Plain in southwestern Australia. These are discussed with respect to changes in coastal sedimentation style through the Quaternary, facies variation in the limestones, age structure of the Pleistocene limestones, longevity of the offshore ridge, and position of former sea levels.

Changes in Coastal Sedimentation Style

The palaeogeographic and stratigraphic record for the Late Pleistocene to the Holocene indicates large changes in coastal sedimentation style (both in terms of coastal geomorphology and lithofacies patterns) through the Quaternary. Coastal sedimentation style in terms of geomorphology alternated between cuspate forelands, wave-built platforms, and barriers. Today, the Yalgorup Plain is the Pleistocene hinterland to the Leschenault-Preston coastal sector (SEARLE and SEMENIUK 1985), a sector dominated by a Holocene barrier dune with an estuarine lagoon to leeward (SEMENIUK, 1985). Sedimentation in this same sector during the Pleistocene mostly involved narrow, low relief beachridge plains overlying beach and seagrass bank facies, similar to the modern coastal zone in the adjoining Cape Bouvard-Trigg Island Sector to the north. The change from prograded beachridge plains during the Pleistocene to barrier dune during the Holocene may reflect the progressive diminution of the offshore barrier through cumulative marine erosion. The coastal setting and type of sediments accumulated during the Pleistocene are similar to Holocene beachridge plains elsewhere in the region, i.e. the Rockingham-Becher area; however, there are differences, due mainly to the ancestral geomorphic setting. The differences are: (1) Pleistocene sedimentation took place behind a barrier ridge situated only 5 km offshore from the palaeo-hinterland and formed a narrow coastal plain 3-5 km wide, whereas in the modern setting the ridge is 10 km offshore and the prograded plain is up to 10 km wide; and (2) individual Pleistocene depositional units were laterally more extensive along the coast, covering a distance of at least 60 km, while the modern example covers a coastal length of 40 km.

Variation in coastal sedimentation style during the Pleistocene, in terms of lithofacies patterns related mainly to the alternation of carbonate-rich and carbonate-poor sedimentation to form limestone formations and quartz sand bodies, respectively. This alternation may have been related to changes in sea temperatures. At this stage, the age of the Pleistocene units is unknown; and hence the relationship of these sedimentary patterns to a global chronology in relation to ^{18}O patterns also is unknown. This area, however, would appear to warrant future research.

Facies Variation in the Limestones

Variation in lithology within the Pleistocene limestone is mainly confined to the submarine facies. The beach and beachridge/aeolian facies throughout the Tims Thicket Limestone and Kooallup Limestone are very similar in structures, sequence of structures, grainsize and fossil content, albeit with variation in quartz content from south to north, as mentioned above. While the submarine facies present a generally similar suite of fossil molluscan components, their structural and textural variation within the limestones (*viz.*, bioturbated foraminiferal calcarenite, shelly/bioturbated calcarenite, laminated shelly calcarenite/coquina, and laminated and cross-laminated marine calcarenite) would appear to be primarily related to location within the coastal setting in terms of protection from wave action. Protected areas accumulated sediment under seagrass cover and would have contained a complement of associated benthos which bioturbated the sediment, forming bioturbated/shelly and bioturbated foraminiferal rich sediments. Less protected areas with seagrass cover may have had a similar faunal component, but more consistent wave action would have resulted in constant physical reworking, forming laminated shelly calcarenite/coquina. Wave-agitated areas without seagrass cover, which perhaps received sand mobilised from adjoining areas, developed into megarippled and sand-wave environments, forming laminated and cross-laminated calcarenite.

Two situations would lead to more, or less, exposure to wave action: location in relation to the gap in the offshore reef systems and height of the palaeo-sealevel. Exposure to wave action through the reef gap would result in a dominance of laminated shelly calcarenite/coquina and laminated to cross-laminated calcarenite in central areas of the Pleistocene limestone systems. A higher sea level would result in more wave trains passing through the offshore reef system and hence a more wave-agitated shoreface along the mainland shore. This would mean that sediments of the Kooallup Limestone, formed with palaeo-sealevel 1.0-1.5 m higher than those formed during deposition of Tims Thicket Limestone, would be more exposed to wave action, and hence laminated shelly calcarenite be more abundant in the Kooallup Limestone. In fact, facies variation within the Pleistocene limestone to a large extent reflect these two situations, with wave-generated marine lithofacies dominating the formerly exposed parts of the terrain of both Youdaland and Kooallupland and dominating the southern Kooallup Limestone sections (Table 3).

Of course, there are numerous other factors in addition to wave exposure discussed above that would contribute to the overall variability of sedimentation and geomorphic patterns in this area, but these would be too difficult at this stage to unravel. These additional factors would include: (1) the effects of palaeo-temperature of the marine waters, and its influence on faunal diversity, productivity, and carbonate production rates; (2) the rate of sedimentation as determined by longshore transport, local carbonate productivity and erosion of the offshore reefs; and (3) the sculpturing of coastal form as related to wind directions and prominence of offshore structures. A total picture balancing the combined effects of sea level, ancestral palaeo-topography, climate, and local tectonism, however, is beyond the scope of this paper. At this stage, much of the variability of submarine facies, in terms of their geomorphic expression, sedimentary structures and textures can be explained, as discussed above, simply in terms of exposure to wave climate within the context of a window to swell and wind waves between the Bouvard and Buffalo reef trends (Figure 8).

Age Structure of the Pleistocene Limestone

The reconstruction of palaeogeography, the stratigraphic relationships between limestones under the Yalgorup Plain, and the pre-existing aeolianites provide information on the age structure of Pleistocene limestone in this coastal area. The succession of units within the Yalgorup Plain show a

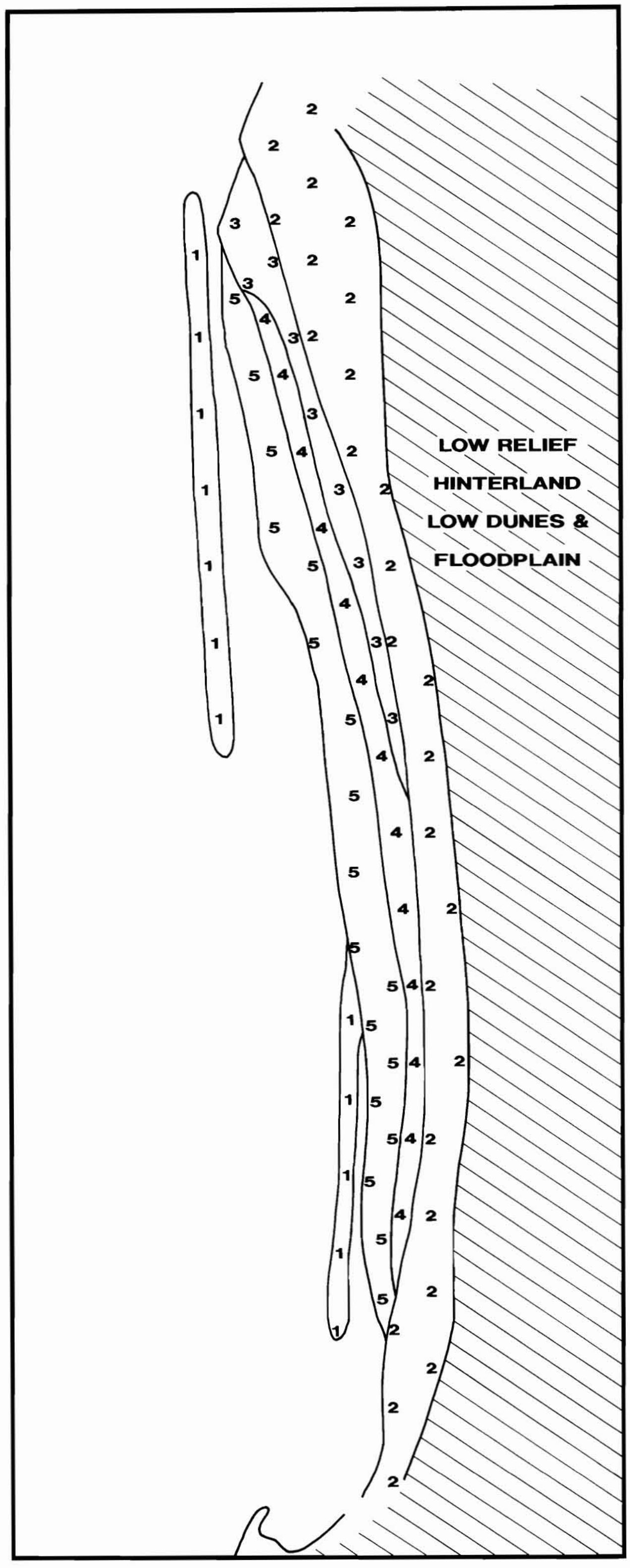

Figure 10. Age structure of the Plesistocene limestone systems.

westward accretion and hence a younging to the west, and thus the youngest limestone in this area is the most westward, the Kooallup Limestone. However, an older aeolianite ridge that helped develop the sedimentation style in this area occurs as a distinct ridge line even further to the west. The relative age structure of the Pleistocene limestones in this area is schematically illustrated in Figure 10 and indicates that the successive ridges and units of the Pleistocene need not become younger progressively from east to west as has been assumed traditionally (*e.g.*, McArthur and Bettenay, 1960). Rather, the age structure and internal relationships of lithologies within the Pleistocene limestones in this region demonstrate a more complex pattern than simple younging of formations and landforms from east to west. Although the ancestral Mandurah-Eaton Ridge and the offshore Pleistocene ridge lines that formed the geomorphic framework to the sedimentation on the Yalgorup Plain may have initially been of similar relative relief, the seaward ridge with progressive erosion has been diminished. Ultimately, an offshore ridge through erosion may become quite negligible in terms of stratigraphic distinction, as evidenced in the subdued/buried ridges in the south of the area, so that the original hinterland ridge and the prograded sand plain become the prominent geological units.

Longevity of the Offshore Ridge

Two events can terminate the effectiveness of offshore ridges, erosion and burial. As described above, the limestone ridges that stimulated growth of the Pleistocene cuspate forelands have been diminished through erosion over time and may now be able to trap only limited/isolated cusps of sand. This raises questions as to how long the offshore ridges persist as structures that can influence coastal sedimentation. The Bouvard and Buffalo ridge lines existed before the building of the Mandurah-Eaton Ridge. This points to their overall antiquity. Furthermore, they have been subject to several phases of marine erosion; during this late Pleistocene phase of the Quaternary in this area, it is apparent that the sea reached approximately the same level during each transgression; and the ridges functioned as offshore barriers for each of these episodes, and thus would have been subject to cumulative effects of marine erosion. Yet they are still extant, though diminished in size, or buried by Holocene deposits. In fact, these offshore ridges could still function as rocky reefs today, again localizing cuspate foreland accretion in more or less the same locality, dependent of course on the height of sea level. Hence they have to be viewed as long-term features that can influence sedimentation patterns through several marine transgressive phases in the Quaternary. However, if cuspate foreland progradation proceeds to the extent that these offshore ridges are "captured" by low beachridge plains, then they can longer function as barriers; and any further accretion would not be directed towards cuspate foreland sedimentation. Currently, the southern ridge that stimulated growth of cuspate forelands in Kooallupland is buried by a Holocene barrier dune system. This Holocene cover is a large ridge in its own right, and if it cemented and retained its topographic relief, it would form a formidable barrier for the next transgression.

Position of Former Sea Levels

Sea level indicators with the Pleistocene formations suggest that each stage of Pleistocene sedimentation took place with a specific stand of sea level. During Youdaland time, relative sea level stood at *c.* 3 m above present MSL. During deposition of the Myalup Sand, relative sea level stood at *c.* 2-3 m below present MSL. During Kooallupland time, relative sea level stood at *c.* 4.5-4.0 m above present MSL, with a progressive fall in sea level following the initial transgression. These sea level positions are relative, because it is not known by how much, if any, tectonism has moved the sequences since the Pleistocene (*cf.* Semeniuk and Searle, 1986b; Playford, 1988).

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□ RÉSUMÉ □

La plaine de Yalgorup est une plaine côtière bien conservée, du Pléistoene tardif, située dans le bassin de Perth, au sud-ouest de l'Australie. Sea succession de sédiments calcaires et siliciclastiques montre qu'au Pléistocène, le processus sédimentaire paléo-côtier a été dominé par d'étroites plaines littorales à crêtes longitudinales, qui se sont dévéloppées sous la forme d'un ruban de dépôts littoraux et des caps incurvés à l'abri d'iles-barrières calcaires et de récifs rocheux situés au large. La clef de l'interprètation des séquences sédimentaires du Pléistocène, de l'histoire des variations de niveau marin dont elles témoignent, réside dans l'examen des modèles holocènes présents dans la même région—en particulier dans la géomorphologie et la stratigraphie de types de côtes tel que dune-barrières, lagons-estuarins et plaines littorales à crêtes longitudinales et caps incurvés de grandes dimensions, ainsi que dans la stratigraphie à petite échelle des séquences plage/dunes, des séquences de pentes littorales, des côtes rocheuses et des bancs d'algues.

La sédimentation s'est produite à l'intérieur d'un chenal linéaire entre une crête et une double rangée de récifs calcaires situés au large de la côte. A Yalgorup, l'évolution en plaine côtière s'est déroulée en plusiers etapes, liées à des périods de stagnation du niveau marin durant le Pléistocène: (1) formation, au Pléistocène, d'une première plaine littorale calcaire à crêtes longitudinales (Youdaland), pendant laquelle une accumulation de débris d'algues calciques a formé une plage ou des crêtes littorales/dunes: (2) accumulation de barrières côtières de sable à forte teneur en quartz (plate-forme sableuse de Myalup et crête sableuse de Myalup); (3) formation d'une plaine littorale calcaire à crêtes longitudinales du Pléistocène plus recent (Kooallupland), dans laquelle, là encore, l'accumulation de débris d'algues calciques a formé une plage ou des crêtes longitudinal/dunes.

Deux ensembles de conditions ont déterminé une progradation plus marquée: une intense production de carbonate de calcium accompagnée d'un apport sédimentaire suffisant, et un abri contre les trubulences de la haute mer, tel qu'une crête formant barrière. Lorsque la production de carbonate était réduite, le sable quartzeux du sud de l'arrière-côte, refaçonné par les turbulences côtières, a été entraîné vers le nord, format une plate-forme sableuse le long du littoral et une barrière de sable, mais cette phase n'a été marquée par aucune accrétion et progradation sensible. Le résultat de cette étude enrichit notre connaissance de: l'histoire du Bassin de Perth, sud-ouest de l'Australie, pendant le Quaternaire; les alternances de sédimentation calcaire et silicilastique en général; le contrôle exercé sur la géométrie des formations sédimentaires côtières par la topographie préexistante; la durée d'existence des crêtes calcaires dans la topographie préexistante; et la structure de datation des plaines côtières du Pléistocène.

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