Quaternary geology, landforms and wetlands between Dawesville and Binningup – description, key features, and geoheritage significance

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October 2009

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1.0 Introduction

The Department of Environment and Conservation invited the V & C Semeniuk Research to undertake a desk-top study of the Quaternary geology, landforms and wetlands between Dawesville and Binningup, providing a description of the geology, noting its key features, and outlining any features of geoheritage significance.

The background to this study is that the coastal region between Mandurah and Bunbury is under increasing residential development pressure, and the area is particularly sensitive as it contains the largest coastal reserve (Yalgorup National Park), coastal wetlands which are part of the Peel-Yalgorup wetland system recognised as a "Wetland of International Importance" under the Ramsar Convention, Thrombolite Communities, regionally significant fauna populations and maintains large areas of Tuart forest and other coastal vegetation largely developed or degraded on much of the Swan Coastal Plain.

The Environmental Protection Authority proposed therefore to develop strategic advice under Section 16e of the *Environmental Protection Act 1986* to provide advice on its position on acceptable development in the region.

The Study Area for this report is defined by Tim's Thicket Road forming the northern boundary, Old Coast Road forming the eastern boundary, Buffalo Road the southern boundary and the Indian Ocean the western boundary; for the geology and coastal geomorphology, the western boundary will be several kilometres offshore on the inner continental shelf within the Indian Ocean. (Figure 1). This aggregate of geological and landform units will be referred to as the Study Area throughout this report.

Overall, the project aims to provide description of environmental features (flora, fauna, coastal geomorphology and hydrology), based on desktop and more detailed research information, which may be utilised to develop strategic advice.

This report provides the information on geology and some coastal geomorphology as part of Phase 1 of the regional project.

Figure 1: Outline showing extent of the Study Area

2.0 Scope of study

The Study Area is defined by Halls Head (southwest of Mandurah), the Old Coast Road forming the eastern boundary, and Buffalo Road forming the southern boundary, and for the geology and coastal geomorphology, the western boundary is several kilometres offshore on the inner continental shelf within the Indian Ocean. Aspects of the Mandurah-Eaton Ridge, where relevant, as it is part of the regional setting of the Study Area, are addressed.

Following the framework provided by the Department of Environment and Conservation in the *Brief to the Project*, the study involved the following:

1. desktop study utilising provided/requested data and search of published or unpublished studies of the project area, or areas outside the project area that have impact on the status of features within the project area;
2. description of the Quaternary geology of the area, encompassing its geological history from the Mandurah-Eaton Ridge to the nearshore continental shelf;
3. discussion of significant geological features, at International, National, and State levels within the Study Area, and how they are reflected in the biotic elements such as thrombolites;
4. discussion of landforms and soils within the Study Area and the impact on landform stability, *e.g.* massive limestone features, mobile dune systems;
5. discussion of significant environmental features within the Study Area, *e.g.* Yalgorup Lakes system and stromatolites/thrombolites, their relationship to the underlying geology;
6. discussion of opportunities and constraints within the project area based on geological/landform/soil environment and usage pressure.

3.0 Structure of report

This report is structured as follows:

4.0 Description of regional setting to place the Study Area in perspective
5.0 Description of the main processes (past and present) that developed the area
6.0 Description of the Quaternary geological features in the Study Area
7.0 The key Quaternary features in the Study Area
8.0 National and International comparisons of the Study Area
9.0 Geoheritage of the Quaternary features in the Study Area
10.0 Discussion and conclusions

4.0 Regional setting

The Study Area is located along the western margin of the Swan Coastal Plain, which is the Quaternary surface of the Perth Basin.

In a temporal and regional context, the Perth Basin is a sedimentary basin today extending in a south-north direction from the Scott Coastal Plain and D'Entrecasteaux region to Northampton, bound on its eastern margin by the Darling Fault. The Darling Fault separates the Phanerozoic sedimentary rock and sediment-filled Perth Basin from the Precambrian rocks of the Yilgarn Craton that underlies the dissected plateau of the Darling Plateau (Figure 2). The Perth Basin has been subsiding along the Darling Fault (approximately marked today by the Darling Scarp) for at least 200 million years accumulating over 5000 m of sedimentary material. In the past 1.5-2.0 million years, *i.e.*, the Pleistocene and Holocene of the Quaternary Epoch, there has been accumulation of sedimentary materials in the upper parts of the Perth Basin as alluvial fans, alluvial flats, riverine channel deposits, desert sand deposits, near-shore marine deposits, coastal sands, estuarine deposits, and wetland deposits, that form the upper sedimentary deposits of the Perth Basin up to 100 m thick. The surface expression of these materials as depositional, relict, and erosional forms is the modern and Pleistocene surface of the Swan Coastal Plain.

The Swan Coastal Plain, named as such by Fairbridge & Gentilli (1950), thus, is the terrain of sand, limestone, and fluvial deposits that form a coastal strip between the Darling Scarp and the Indian Ocean. In relatively terms, given the height of the Darling Plateau reaching 200-300 m above sea level, the Swan Coastal Plain forms a low land ~ 5m – 90 m in height above sea level between Darling Plateau and Ocean.

Stratigraphically, the Quaternary sedimentary units that underlie the Swan Coastal Plain have been formally named as geological formations, *viz*.,

1. The alluvial fans and (in part) desert dunes along the Darling Scarp = Yoganup Formation
2. The alluvial sediments on the eastern part of the Plain = the Guildford Formation
3. The Pleistocene desert dunes of quartz sand = the Bassendean Sand
4. The Pleistocene coastal dunes (now limestone) = Tamala Limestone
5. The Pleistocene coastal marine to dune deposits (now limestone) = Tims Thicket Limestone and Kooallup Limestone
6. The Holocene coastal dunes = Safety Bay Sand
7. The Holocene coastal coquina (shell gravel) = Preston Beach Coquina
8. The Holocene near-shore marine deposits coastal dunes = Becher Sand
9. The Holocene estuarine deposits = Leschenault Formation

Various other Quaternary formations occurring in local areas underlie the Swan Costal Plain; these include the Ascot Beds, the Peppermint Grove Limestone, the Rockingham Sand, amongst others.

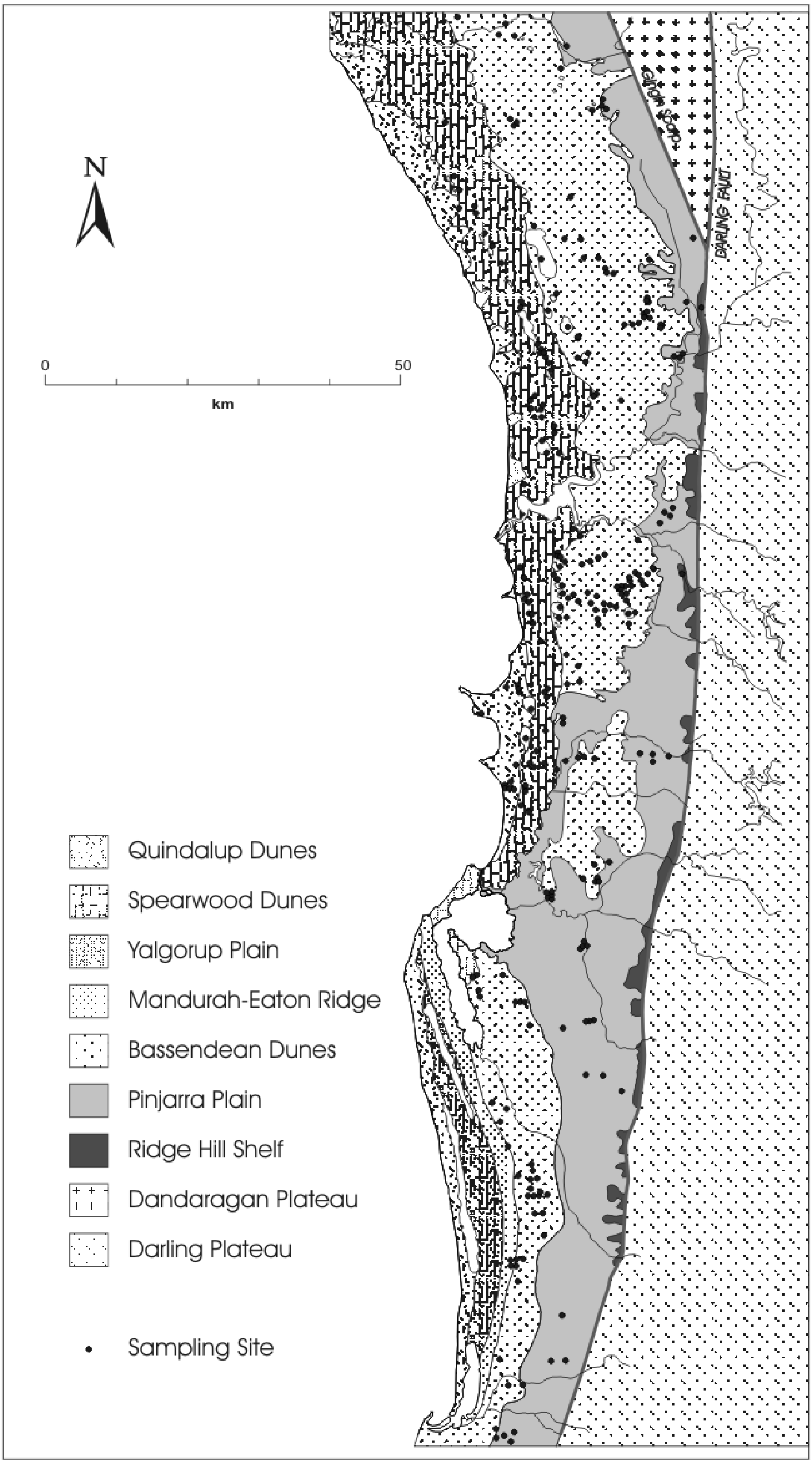

Figure 2: The geomorphic units of the Swan Coastal Plain

The landforms that comprise the Swan Coastal Plain also have been generally formally named, though not all of the landforms that are the surface expression of the sedimentary units have been formally named. Those that have been formally named are listed below:

1. The alluvial fans and (in part) desert dunes along the Darling Scarp = the Ridge Hill Shelf
2. The alluvial sediments on the eastern part of the Plain = the Pinjarra Plain
3. The Pleistocene desert dunes of quartz sand = the Bassendean Dunes
4. The Pleistocene coastal dunes (now limestone) = Spearwood Dunes
5. The Pleistocene coastal marine to dune deposits (now limestone) = the Yalgorup Plain and Eaton-Mandurah Ridge, and subdivided into smaller scale units (see later)
6. The Holocene coastal dunes = Quindalup Dunes

Some of the stratigraphic units have no expression at the surface on the Swan Coastal Plain, *i.e.*, they are wholly subsurface formations, and so axiomatically have no formal landform nomenclature (*e.g.*, the Becher Sand).

A three-dimensional representation of these stratigraphic units and landforms from the Darling Fault of the coast is shown diagrammatically in Figure 3.

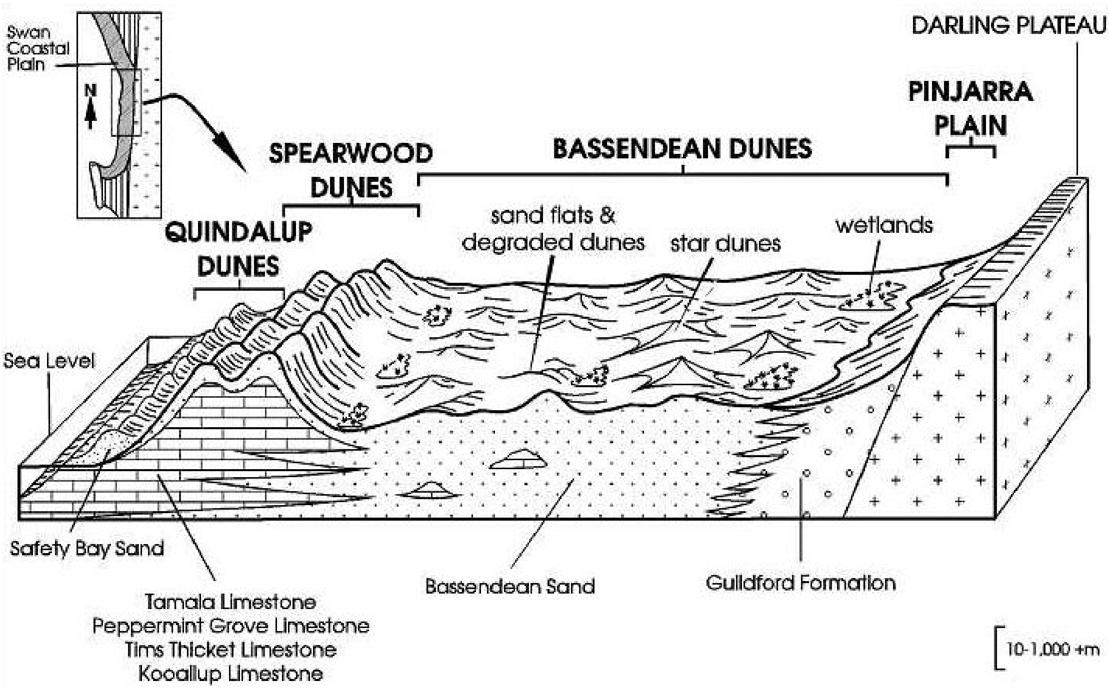

Figure 3: Idealised three-dimensional diagram of the Swan Coastal Plain showing landforms, stratigraphic units, and relation to the Darling Plateau (underlain by Precambrian rocks)

In the Study Area, the following stratigraphic units and their corresponding surface expression as landform units have been recorded (Semeniuk 1997):

1. The easternmost unit is the Eaton Sand that underlies the Mandurah-Eaton Ridge.
2. The next western unit is the upward shoaling limestone system referred to the Tims Thicket Limestone that underlies a Pleistocene landform termed Youdaland.
3. The next western unit is a quartz shoestring deposit referred to the Myalup Sand that underlies a Pleistocene landform termed Myalup Sand Ridge and Myalup Sand Shelf.
4. The next western unit is the upward shoaling limestone system referred to the Kooallup Limestone that underlies a Pleistocene landform termed Kooallupland.
5. The most western unit is the barrier dunes of the Safety Bay Sand that forms the seafront of the Study Area.

The distribution of these units are shown in Figures 4 & 5.

In a regional context, the entire package of stratigraphic units and landform units listed above occur within a broad scale low-amplitude embayment or plan concavity cut into the Bassendean Dunes, and demarcated by the broadly arcuate form of the Mandurah-Eaton Ridge. The broad concavity was the Western Australian coast line for four Pleistocene sedimentary episodes, and was anchored between the Bunbury Basalt to the south and the Limestone rocky shore of Halls Head to the north. The Pleistocene to Holocene sedimentary units over the interval of five interglacial sedimentary periods have progressively filled the broad concavity along the coast (Figure 6).

The sedimentary sequences preserved in the Pleistocene limestone units record a sedimentary history, for each of the inter-glacial periods when sea level stood approximately where it is now, of seagrass bank sedimentation, capped by a beach/dune sequence. The limestones record climate conditions of “Perth” style climate and sedimentation for the Tims Thicket Limestone, and “Dongara” style climate and sedimentation for the Kooallup Limestone, with sedimentation in cuspate forelands leeward of limestone reefs (similar to that forming in the Rockingham-Becher beach ridge plain). The Myalup Sand records development of a barrier (similar to the modern Coorong in South Australia) that was carbonate-depauperate, *i.e.*, quartz-rich, and similar in climatic setting to Albany. As such, importantly, the sequence of sedimentary packages progressing during inter-glacial periods from east to west thus records deposition along a shoreline during an inter-glacial period but with different climates. That is, though the overall climate was relatively humid and warm compared to the glacial period when sea levels were at a low-stand, the climate for a given depositional episode was different (T A Semeniuk 2005). The Tims Thicket Limestone depositional episode was within a climate similar to Perth today The Myalup sand depositional episode was within a climate similar to Albany today (that is, colder than the Dongara and Perth climates). The Kooallup Limestone depositional episode was within a climate similar to Dongara today (that is warmer than an Albany setting, and a Perth setting).

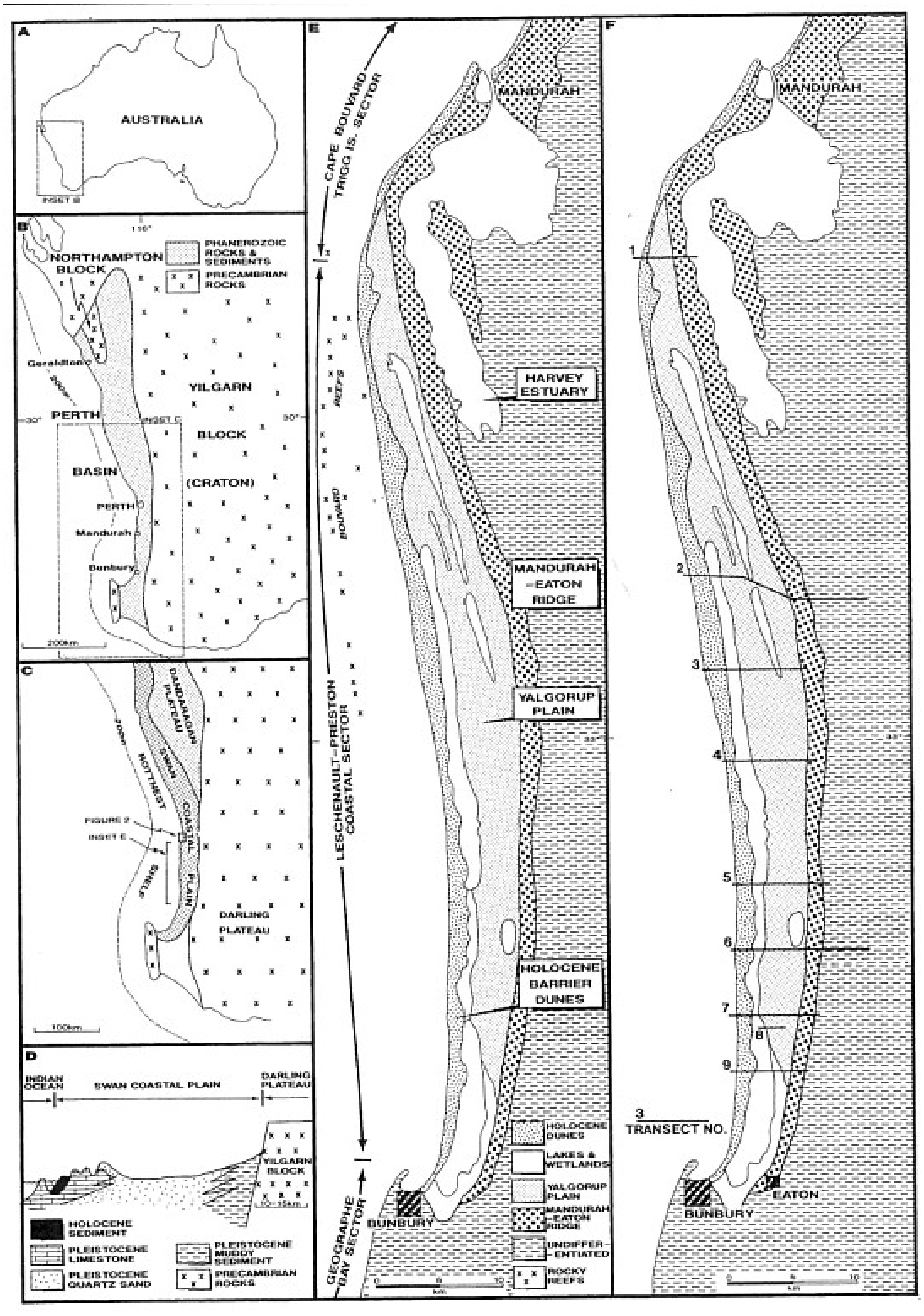

Figure 4: Main landform units in the Mandurah to Bunbury area incorporating the Study Area (after Semeniuk 1996)

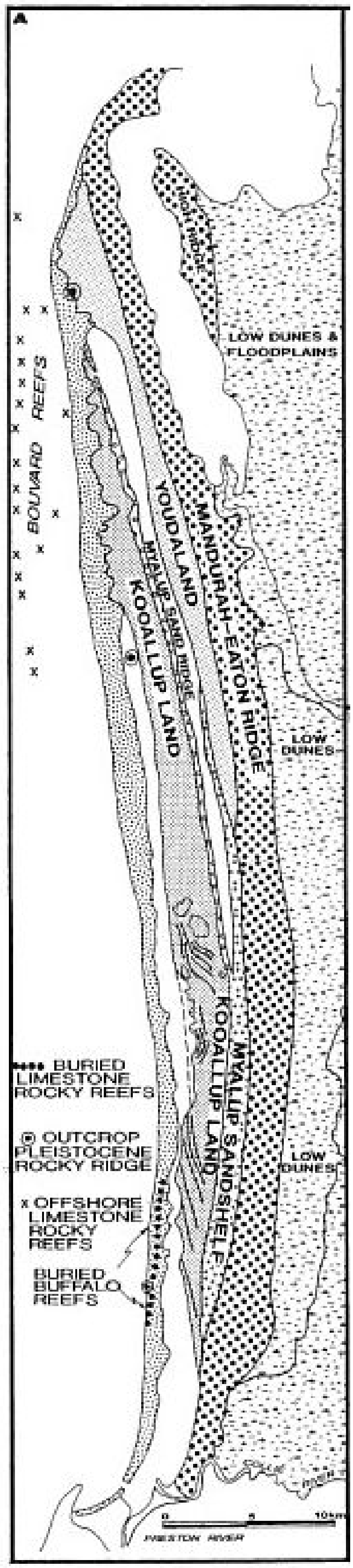

Figure 5: Stratigraphic units and their corresponding surface expression as landforms (after Semeniuk 1996)

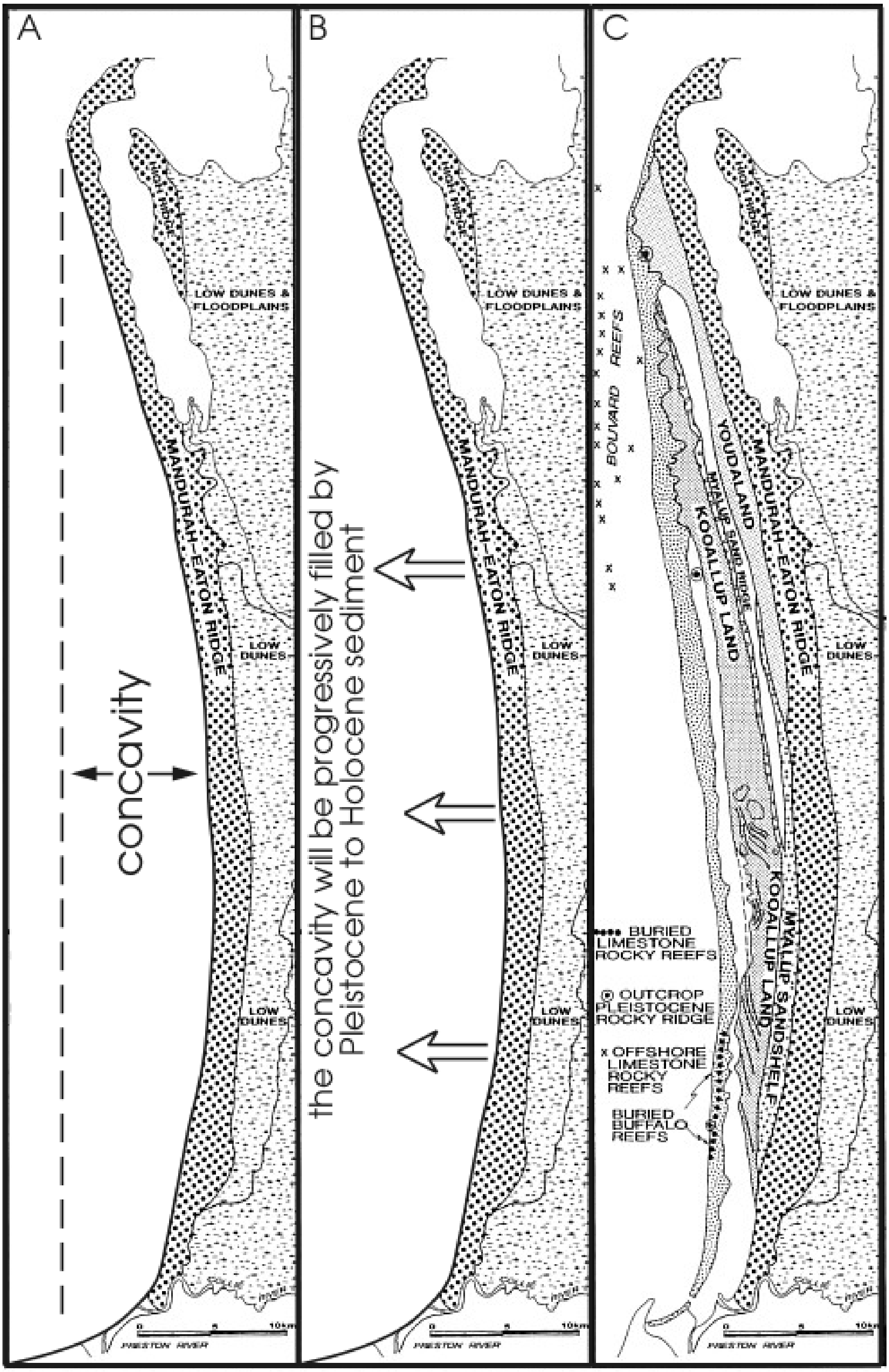

Figure 6: Concavity in the regional coast, with filling of the concavity by progressive sedimentation during the Pleistocene and Holocene.
(modified after Semeniuk 1996)

The modern barrier, the Leschenault-Preston Barrier, represents barrier dune sedimentation within the modern inter-glacial regime.

In a coastal context, the Study Area is mainly located in the Leschenault-Preston Sector and partly in the southern part of the Bouvard-Trigg Island Sector of Searle & Semeniuk (1985); see Figure 7.

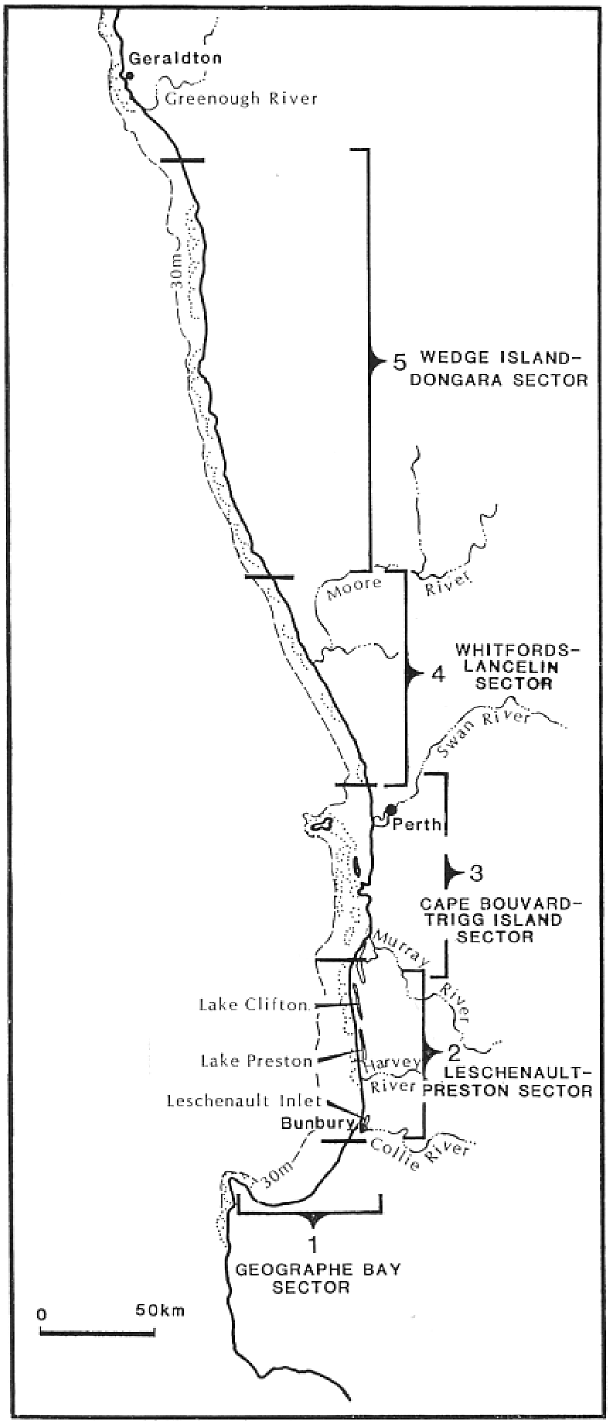

Figure 7: The coastal sectors of Searle & Semeniuk (1985), with the Study area mainly located in Sector 2 and partly in Sector 3.

In the marine near-shore environment, the Study Area is comprised of a limestone pavement shelf, comprised of lithified Pleistocene marine shelf sediments, with veneers of sand, and encrustations of hard bottom communities (Searle & Semeniuk 1985; Collins 1988). In the marine near-shore environment, north of the Study Area, there are two marine limestone ridges, the (outer) Five Fathom Bank, and the (inner) Garden Island Ridge (Searle & Semeniuk 1985), the latter variably emergent above the water level (ranging from submerged rock reefs, to submerged rocky reefs and small islands, to large Islands like Garden Island). The southern extension of the Garden Island Ridge (Searle et al 1987) intersects the coast at Halls Head (Semeniuk 1995). The southern extension of the ridge of the Five Fathom Bank (Searle et al 1987) forms the Bouvard Reefs and intersects the coast just south of the Bouvard Reefs (Semeniuk 1995). Further south of the Bouvard Reefs, the Western Australian coast is offshore barrier-free and exposed directly to swell and wind waves resulting in the development of a barrier dune system along the shore (the Preston-Leschenault Barrier).

As such, for the tract of coast between Halls Head and Bunbury, the coast is relatively bathymetrically simple between Bunbury and the Bouvard Reefs, and bathymetrically complex in the near-shore in the region of the Bouvard Reefs.

The bathymetrically complex near-shore environment had implications in the Holocene history in this part of the coast.

Various types of wetlands have been developed in the Study Area, ranging from lakes to water logged basins. The majority of the wetlands have been developed along the interfaces between the major stratigraphic units. However, some of the wetlands have been developed as perched types on calcreted limestones, some as karst features and some as intra-dune in a Pleistocene beach ridge terrain. Wetland types will be described in more detail in a later section.

Note that in the Study Area there is a general lack of fluvial drainage.

5.0 Main processes - past and present

The main processes that have operated in the past during the Pleistocene and that are operating in the present to develop the stratigraphic units and landforms in the Study Area are described below. This description does not deal with small scale processes and products such as micro-solution, or carbonate mineral precipitation, and other diagenetic products, but rather with the larger scale processes and products that have been instrumental in shaping and developing stratigraphic units and landforms. The main processes are listed generally chronologically as a series of "events":

Pleistocene past event: accumulation of marine sediments on the shelf, and their lithification to form a sheet of fossiliferous limestone (shelly limestone).

Pleistocene past events: globally-widespread glacial and inter-glacial cycles alternating generally on a 100,000 year pattern that, in the Study Area, have resulted in alternating coastal sedimentation during inter-glacial periods and terrestrial (desert) sedimentation during glacial periods, and resulted in sea level rising and falling in response to the alternating inter-glacial and glacial periods.

Pleistocene past events: accumulation during inter-glacial periods of near-shore and coastal marine deposits and related coastal dunes that lithified to form shore-parallel coastal limestones, followed in turn by the development, during the intervening inter-glacial period, of karst, weathering profiles and calcrete on the coastal limestone; in this context, there have been four inter-glacial sedimentary events during the Pleistocene period, the first being the development of the Eaton-Mandurah Ridge as a shoreline sand barrier, dominated by quartz sand, with local calcareous sand lenses (now local limestone lenses; Semeniuk & Glassford 1987); the second being the development of beach ridge coastal plain formed by the upward shoaling of seagrass bank sediments, beach sediments, and coastal dunes (lithified to form the Tims Thicket Limestone; Semeniuk 1995), in a broad wedge-shaped body with the maximum sedimentation located to the northern sector of the Study Area; the sedimentation style involved complex cuspate foreland progradation; the third sedimentary event being the development of a shore-parallel quartz sand narrow coastal dune barrier (forming the stratigraphic unit the Myalup Sand); then fourth being the development of younger beach ridge coastal plain formed again by the upward shoaling of seagrass bank sediments, beach sediments, and coastal dunes (lithified to form the Kooallup Limestone; Semeniuk 1995), in a broad shore-parallel ribbon-shaped body with the maximum sedimentation located to the middle and southern sector of the Study Area; the sedimentation style, again, as with the Tims Thicket Limestone, involved complex cuspate foreland progradation. Each of these inter-glacial depositional events was developed with sea level more or less similar to that of today (in comparison to the levels it was during the glacial period), but in detail with sea level in different positions. The Tims Thicket sedimentary accumulation took place with sea level initially about 4.5 m above its modern present level and falling with progradation to about 3.0 m above its modern present level. The Myalup Sand sedimentary accumulation took place with sea level about 2-3 m below its modern present level. The Kooallup sedimentary accumulat6ion took place with sea level about 3.0 m above its modern present level. Also, each of these inter-glacial depositional events was separated by glacial period weathering and karst development.

A summary of these past Pleistocene events is shown in Figure 8.

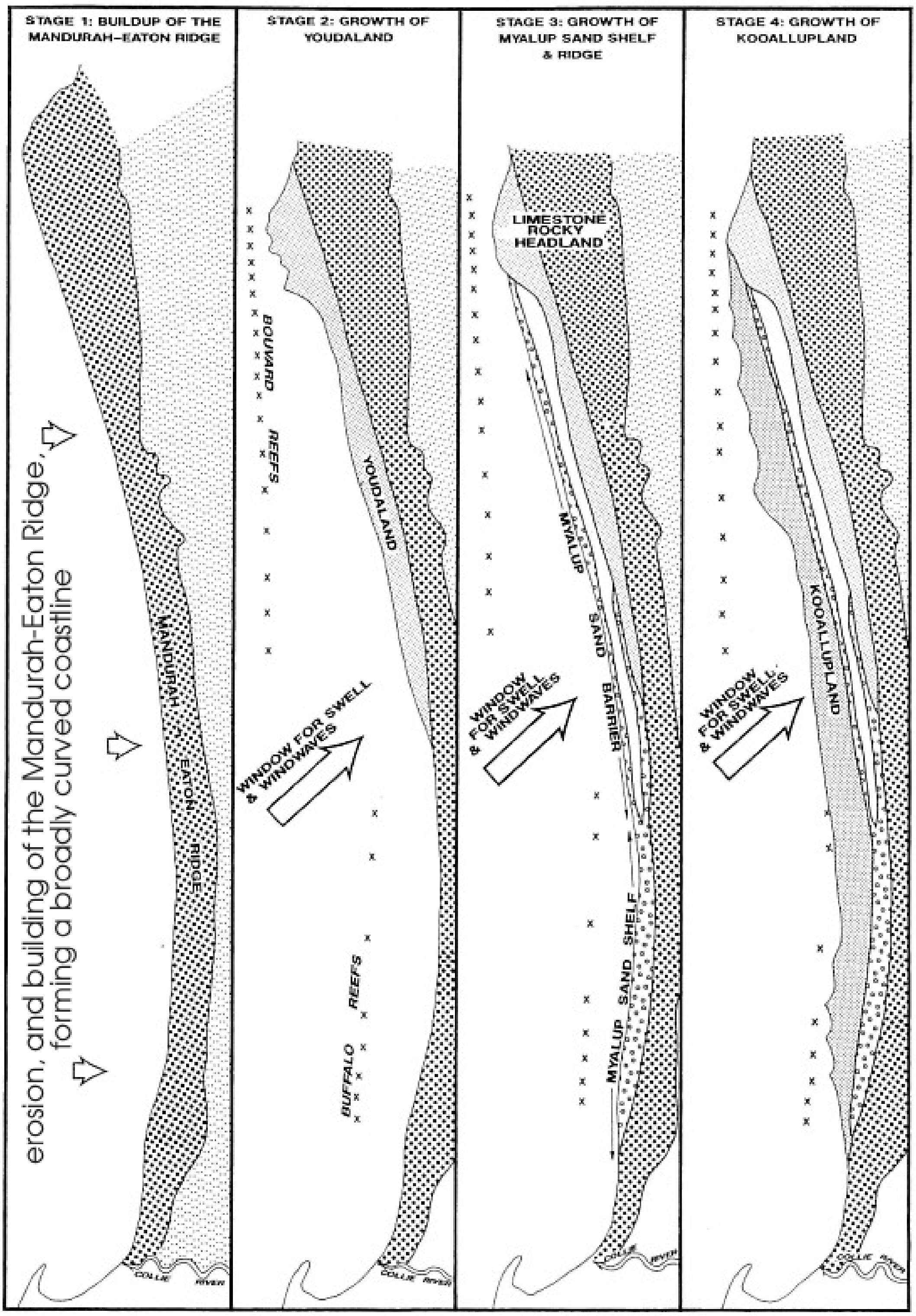

Figure 8: Pleistocene events leading to the development of the Mandurah-Eaton Ridge and the Yalgorup Plain (after Semeniuk 1997)

Holocene past events: the past 7000 years, during the early to middle Holocene involved development of a linear barrier dune system that barred a large linear lagoon that extended from Bunbury to near Preston Beach (Figure 8). Under the effects of swell and wind waves driving coastal erosion, and onshore winds driving inland dune ingression, this barrier migrated eastwards for several kilometres over 7000 years, progressively exposing at the seaward base of the barrier the estuarine and lagoonal deposits that formed in the protected zone to leeward of the barrier. In addition, in its eastern migration, the barrier locally impinged on to the most westward projecting parts of the limestone terrain on Kooallupland, thus segmenting the large linear lagoon that extended from Bunbury to near Preston Beach into two water bodies: a northern part now called Lake Preston, and a southern part called Leschenault Inlet estuary (Figure 9). The Holocene barrier, however, is not stratigraphically and geomorphologically simple, in that it has been subject to a quite variable sea level history. In the northern part of the Leschenault-Preston Barrier, leeward of the Bouvard Reefs, with sea level 6 m below its modern present level 8000 years ago, coastal sedimentation commenced with accumulation of a package of sediment in a cuspate foreland, then with sea level rising to about 2 m below its modern present level about 7500 years ago, and there was the beginning of the development of the dune barrier that extended from the Bouvard Reefs area to Bunbury. And then with sea level rising to 3 m above its modern present level some 5000 years ago, and progressively dropping to the present position, there was progradation of shore with accumulation of the Preston Beach Coquina to the north, and shelly sand in the Leschenault Peninsula area, with a final retreating dune phase throughout the entire Leschenault-Preston Barrier. The result is a complex stratigraphy under the barrier, in fact one of the most complex barrier stratigraphy globally (Semeniuk 1996) with four separate formations developed under the barrier (*viz*., the Becher Sand, the Preston Beach Coquina, the Leschenault Formations and the Safety Bay Sand).

It is clear from the above history and description of regional setting that glacial and inter-glacial events and sea level history have been major driving forces in the development of the stratigraphy and terrain of the Study Area. Glacial and inter-glacial events have resulted in major rise and fall of Pleistocene sea level, and the rise of Holocene sea level. During inter-glacial periods, with sea level more or less near its present position, relative to the low levels extant during glacial periods, coastal near-shore marine and coastal sedimentation took place. The Holocene sea level history has been interpreted by Semeniuk & Searle to be due to local tectonism (Semeniuk & Searle 1985).

In the context of a rising and falling sea level during Pleistocene glacial and inter-glacial periods, the various Pleistocene sedimentary bodies with their stratigraphic packages were deposited as follows.

The Tims Thicket Limestone accumulated during an inter-glacial period with sea level 4.5-3.0 m above modern sea level. As such the limestone is generally slightly more elevated in topographic height than the other Pleistocene and Holocene units on the Yalgorup Plain and the Quindalup Dunes, and the hydrological interfaces and calcretes therein are also slightly more elevated in topographic height than the other Pleistocene and Holocene units.

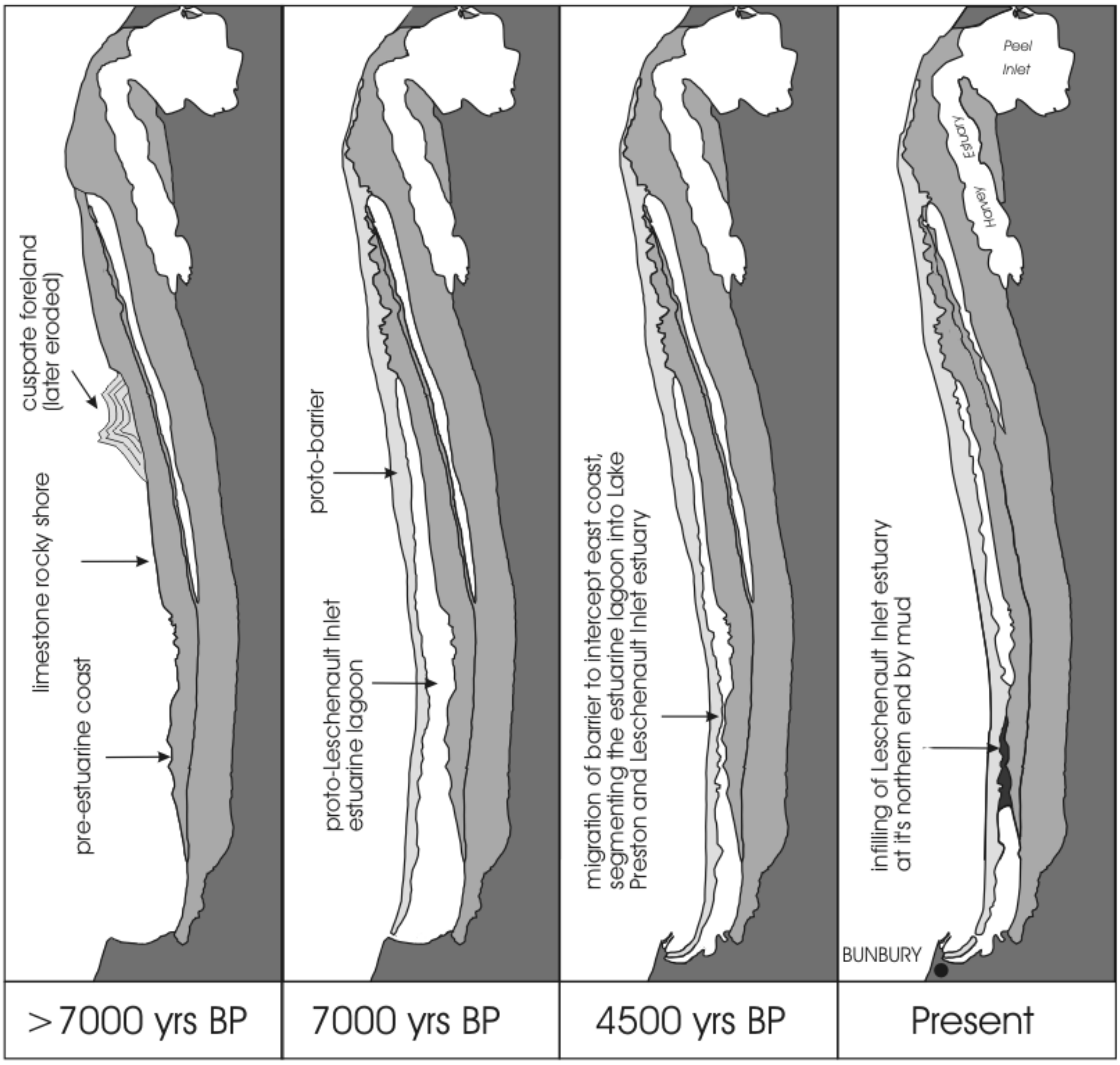

Figure 9: Holocene history, from over 7000 years BP to the present, of the Mandurah to Bunbury zone, showing evolution of the Leschenault-Preston Barrier, in time segmenting the linear lagoon into a northern Lake Preston and a southern Leschenault Inlet.

The Myalup Sand accumulated during an inter-glacial period with sea level about 2-3 m below its modern present level and, as such, the sand stratigraphically is generally lower in elevation than the other Pleistocene and Holocene units. It functions as a hydrological unit that forms a recharge and intake zone relative to adjoining Pleistocene limestone units.

The Kooallup Limestone accumulated during an inter-glacial period with sea level 3.0 m above its modern present level. As such the limestone is generally slightly less elevated in topographic height than the other Pleistocene limestone, but more elevated than the Pleistocene sand (Myalup Sand) and the Holocene units. The hydrological interfaces and calcretes in the Kooallup Limestone are also more elevated in topographic height than the adjoining Pleistocene Myalup Sand and the westerly occurring Holocene units.

Major unconformities between inter-glacial depositional episodes were marked by karstification and calcrete sheet development.

A summary of the accretionary history over the Pleistocene of the evolution of the Mandurah-Eaton Ridge and the adjoining Yalgorup Plain, showing the accumulation of the sedimentary bodies over four stages separated by glacial episodes is shown in Figure 9. The calcareous sedimentary bodies on the Yalgorup Plain were to lithify to become limestone.

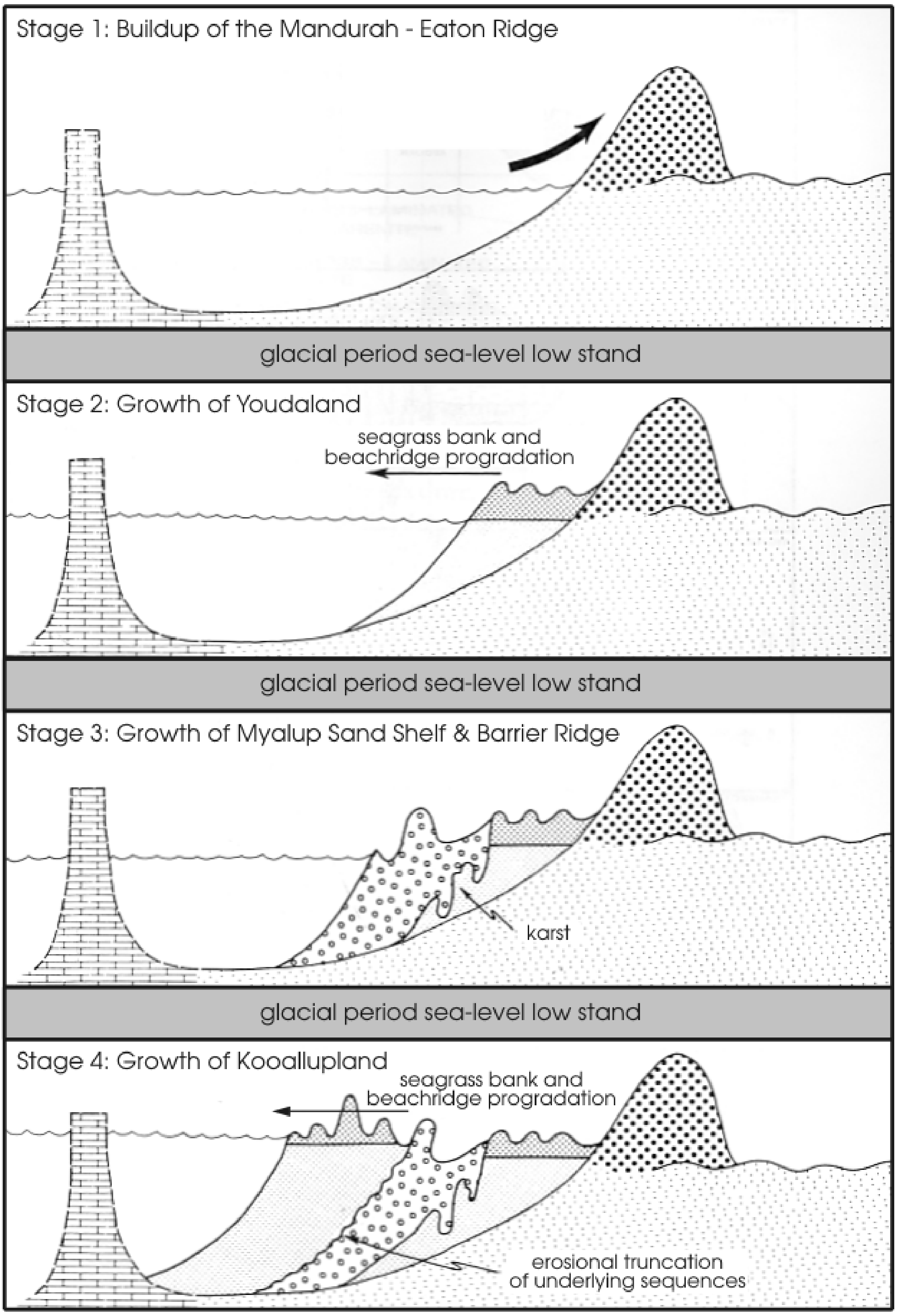

Figure 9: Accretionary history over the Pleistocene of the evolution of the Yalgorup Plain

These limestones, sands, karst surfaces, and calcretes underlying the Mandurah-Eaton Ridge, the Yalgorup Plain, and the Quindalup Dunes of the Leschenault-Preston Barrier form the hydrological framework to the Study Area, with major intake zones (recharge zones) influenced by the occurrence of quartz sand formations, and pipe-punctured limestone, and the transmissivity of the Pleistocene formations determined/influenced by the limestone grainsize, amount of cementation, calcretization, occurrence of calcrete sheets, and macro-karst and micro-karst development.

In the Study area, the complex Holocene stratigraphy also has resulted in a relatively complex hydrological framework compared to barriers that are comprised simply of coastal dune sand: there is dune sand, calcrete sheets, coquina, and, at depth, estuarine sediment.

In the Pleistocene, and in the Holocene, in a coastal setting shoreline processes of wave action (swell and wind waves) and onshore winds have been instrumental in driving the development of Pleistocene and Holocene barriers and their lagoons, and the development of cuspate forelands. Swell and wind waves have emanated generally from the southwest, though with some slight variation in direction both during the Pleistocene and in the Holocene, as manifest by relict dune orientations, and in the accumulation of sand in the shelter of offshore reefs.

The final aspect of description of regional setting in this document is a brief account of the various ways that wetlands have developed in the Study Area.

The modern environment in the Leschenault to Mandurah area, and in the Point Becher area (C A Semeniuk 2007) provides two models of how wetlands form in coastal settings and these models are applicable to some of the wetlands on the Yalgorup Plain. In the first instance, the barrier of the Leschenault Peninsula has barred a lagoon (that is in part an estuarine lagoon; Semeniuk et al 2000). This is similar to the lagoon of The Coorong, barred by the Younghusband Peninsula in South Australia. In the second instance, in the Becher area, wetlands form as primary slacks, formed by spits that bar a portion of the sea isolating them as lagoons (dune slacks or as lakes) from the main ocean, and form with groundwater table rise in swales of beach ridges (C A Semeniuk 2007).

Karst and solution are other mechanisms by which wetlands have formed in the Study Area, and these are the main mechanisms by which Pleistocene and Pleistocene-Holocene wetlands have formed. Details of the wetlands will be described later in this report.

6.0 Description of the Quaternary geological features in the Study Area

The description of Quaternary geological features in the Study Area is outlined in the sections of:

1. mainland geomorphology
2. coastal zone
3. nearshore submarine features
4. stratigraphy
5. hydrology
6. karst
7. wetlands
8. sea level history.

6.1 Mainland geomorphology

The landforms (geomorphology) of the Study Area occurring on the mainland are described below. The coastal zone and the wetlands are excluded from this description and will be described as a separate suite of units. The mainland landforms of the Study Area mainly belong to the Yalgorup Plain, a terrain of Pleistocene limestone. The most easterly landform of the Study Area (and not part of the Yalgorup Plain) is the south-to-north extensive, but relatively narrow, Mandurah-Eaton Ridge. This is a ridge several tens of metres high, dominated by quartz sand, with some limestone lenses (Semeniuk & Glassford 1987). This ridge adjoins the lowlands of Bassendean Dunes (and Bassendean Sand) that occur to the east. The entire Yalgorup Plain (comprised of Pleistocene limestone) has prograded from this sand-dominated ridge. The western land part of the Study area is a south-to-north extensive, but also relatively narrow, barrier of the Quindalup Dunes referred to the Leschenault-Preston Barrier of Searle & Semeniuk (1985).

The Pleistocene landforms have been subdivided and formally named by Semeniuk (1995).

As noted above, the oldest Pleistocene landform, that forms the barrier along the edge of the Bassendean Dunes, and separates the Bassendean Dunes from the Yalgorup Plain, is the Mandurah-Eaton Ridge. It represents a period of coastal barrier dune building. Its western margin is broadly arcuate, with northern and southern extremities anchored by the "headlands" of limestone of Halls Head and the Bunbury Basalt at Bunbury.

The oldest part of the Yalgorup Plain, underlain by marine and aeolian limestone of the Tims Thicket Limestone, is located mainly to the north of the Yalgorup Plain, and forms a series of cuspate forelands with relict beach ridge patterns. This is termed Youdaland ("Youda" Land). The terrain is generally low, and consists of low undulating linear former dunes (now aeolianite).

To west, the next Pleistocene unit, underlain by quartz sand, forms a ridge and shelf, and is referred to the Myalup Sand. It comprises the terrain known as Myalup Sand Ridge to the north of its occurrence, and the Myalup Sand Shelf to the south. The terrain is generally low, and consists of low ridge of sand and a ribbon of sand located between the two Pleistocene limestone formations (the eastern Tims Thicket Limestone and the western Kooallup Limestone).

The youngest part of the Yalgorup Plain, underlain by marine and aeolian limestone of the Kooallup Limestone, is located along the whole length of the Yalgorup Plain, and locally forms a series of cuspate forelands with relict beach ridge patterns. This landform is termed Kooallupland ("Kooallup" Land). As with Youdaland, the terrain is generally low, and consists of low undulating linear former dunes (now aeolianite).

The Leschenault-Preston Barrier is a Holocene barrier dune system. Its surface is dominated by eastward ingressing and eastward ingressed parabolic dunes. The barrier can be subdivided into seven sectors:

1. the southern sector, 1.5-2.0 km wide, is dominated by eastward ingressing parabolic dunes that encroach and bar the southern half of Lake Preston; the dunes are dominantly fixed, though there is a seaward zone of mobile parabolic dunes;
2. the central part, about 3 km long and 2 km wide, is dominated by mobile parabolic dunes forming a strip 1 km wide, that are fronted to the west by a low barrier dune; to the east the terrain is fixed parabolic dunes;
3. the next sector, about 4.0-4.5 km long, extending from the central part to the township of Preston Beach, is similar to the southern sector, being comprised of eastward ingressing parabolic dunes that encroach and bar the northern half of Lake Preston;
4. north of the Preston Beach townsite, and extending for about 2 km, is a zone that consists of a low barrier behind which is a long lowland (a series of coalesced parabolic dune depressions), and an eastern zone of parabolic dunes encroaching/encroached over a platform of Kooallup Limestone – this part of the Leschenault-Preston Barrier does not function as a barrier to Lake Preston;
5. extending 4 km north of the northern shore of Lake Preston, the Leschenault-Preston Barrier consists of seaward strip of beach ridges, and a western strip of eastward ingressing parabolic dunes that encroach upon a relatively flat terrain of Kooallup Limestone;
6. further north, and extending to about the latitudinal level of the northern tip of Lake Clifton, the Leschenault-Preston Barrier no longer acts as a barrier to Lake Preston, and directly encroaches upon the limestone of Kooallupland; here it is about 1.5 km wide, and consists of fixed parabolic dunes;
7. beyond the sixth sector, the Leschenault-Preston Barrier becomes narrow 0.5- about 1 km wide), and directly encroached upon the limestones of Youdaland; it is composed of westerly occurring mobile dune, and easterly occurring fixed dunes.

The complexity of the stratigraphy of the dune barrier along a series of transects from north to south along the Leschenault-Preston Barrier is shown in Figure 10.

Throughout the southern to middle sectors of the Leschenault-Preston Barrier, the eastern margin of the barrier is an elevated platform of sand (similar in form and origin to the "woodland plain" of the Leschenault Peninsula barrier (of Semeniuk & Meagher 1981a). Where parabolic dunes have encroached from the coast to the shore of Lake Preston, it is buried. Where parabolic dunes have not fully extended from the coast to the shore of Lake Preston, the platform is present as a 300-1000 m wide strip of land.

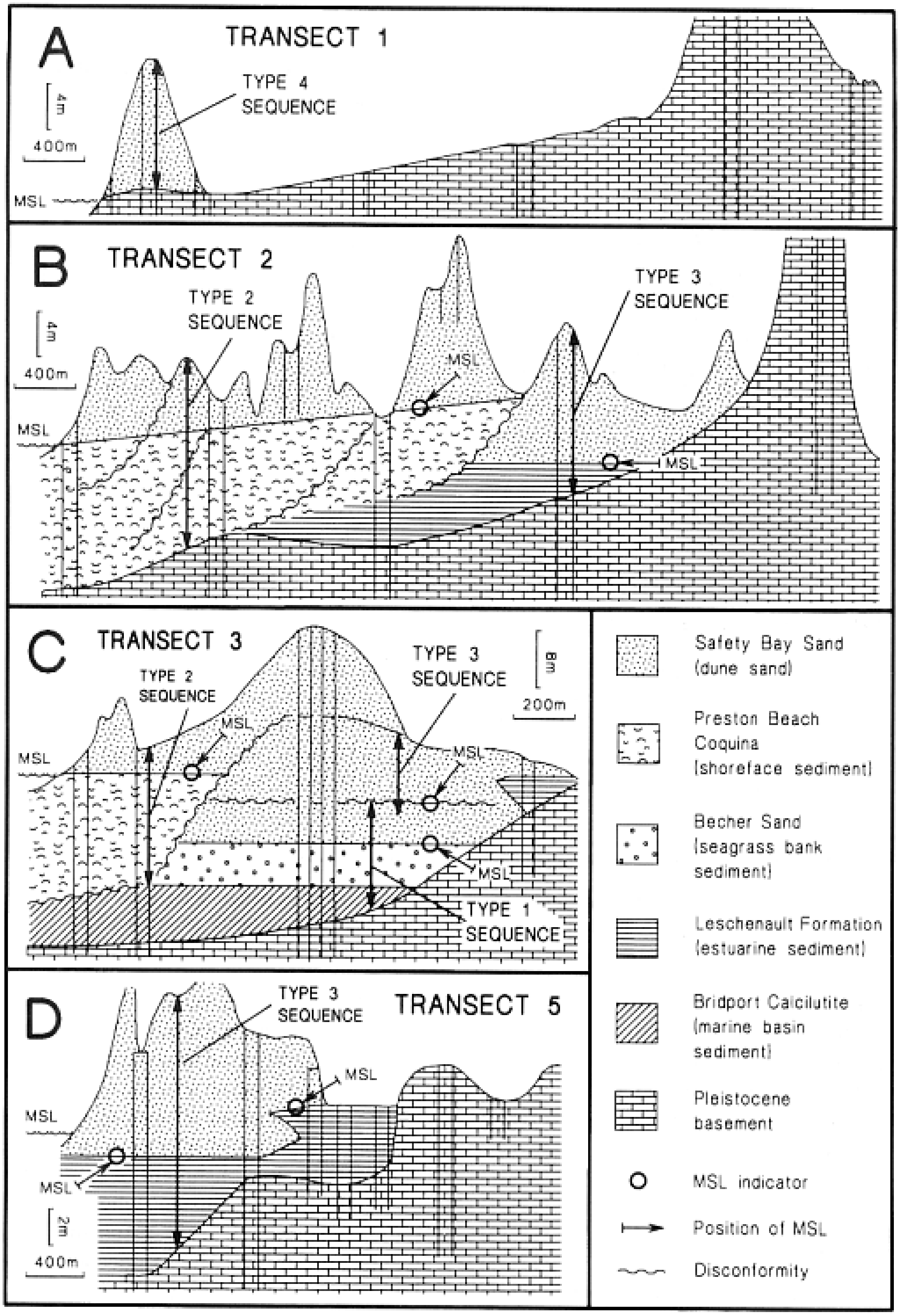

Figure 10: Stratigraphy of the Holocene barrier dune from north (A) to south (D). The Study Area is specifically encompassed by insets B & C (after Semeniuk 1986).

Along the entire length of the Leschenault-Preston Barrier, there is variable development and width and dynamics of the most seaward strip of dunes. There is generally a seaward mobile parabolic dunes of variable width depending on long-term Holocene coastal history. Foredunes also are present along the entire coastal strip, but variable in their development and width.

6.2 Coastal zone

The entire length of the Leschenault-Preston Barrier is wave dominated. It is subject to swell and wind waves, and onshore winds. The detail and form of the coast is variable depending on stratigraphy and local coastal configuration. Mostly the coast is a sandy beach with generally moderately steep face. Locally, because of wave action and northward currents, the shoreface is a gravel shell lag. Local outcrops of Pleistocene limestone occur on the beach and in the shallow water of the beach environment. These limestone outcrops represent topographically higher-than-normal occurrence of the limestone ridge that is the southern extension of the Bouvard Reefs, or higher-than-normal occurrence or outcrops of Kooallup Limestone.

The coastal zone also may manifest occurrences of beachrock. This occurs as weakly indurated limestone in the swash zone and low subtidal zone (Semeniuk & Searle 1986). The occurrence of beach rock and strips of cemented sand in front of the retreating barrier dune in the Leschenault Peninsula area is shown in Figure 11.

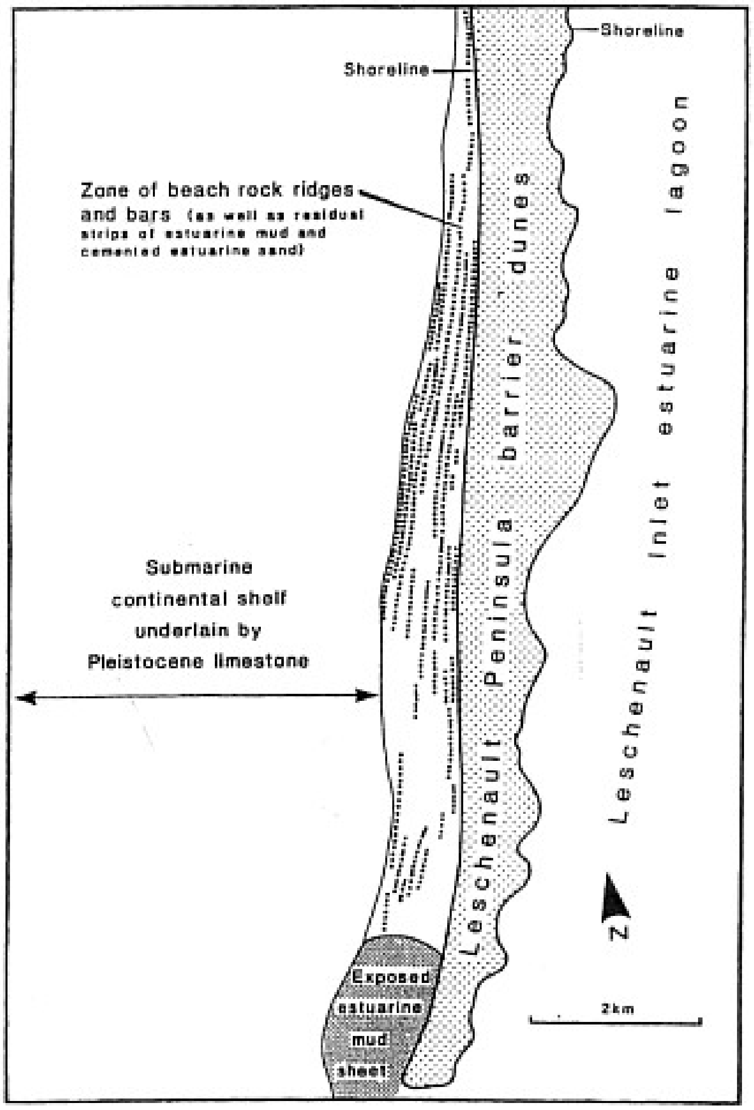

Figure 11: Beach rock and strips of cemented sand in front of the retreating barrier dune in the Leschenault Peninsula (after Semeniuk & Searle 1986)

Elsewhere, locally, and depending on season and the coast may be cliffed, with erosional cliffs cut into the dunes forming a direct seafront to the ocean, with minimal development of a beach, and little of no development of a foredune. Erosion may also bring to the beach front outcrop of calcrete and soils that normally are forming and buried, respectively, under the barrier.

6.3 Nearshore submarine features

The nearshore submarine environment along the western margin of the Leschenault-Preston Barrier, *i.e.*, the inner shallow marine shelf, between low tide and about 10 m depth of water, exhibits a number of features. Generally it is a pavement of Pleistocene limestone that has been wave-planated. Locally, upstanding above this limestone are pinnacles that rise ~ 1 m above the surface of the limestone. The pinnacles are encrusted by foliose algae, coralline algae, and other hard-bottom encrustations and lithophagic organisms. The limestone also exhibits circular (though corroded) pipe openings. The limestone pavement is encrusted by a hard-bottom community of coralline algae, bryozoans, and other skeletal organisms (Collins 1988). There are patches of sand veneer on this limestone pavement. Coralline encrustations centred on lithoclasts and shell fragments, though the rolling action of swell, have developed algal pisolites (also termed oncolites), or flattened oncolites (termed informally as “sea biscuits”). Along inner edge of the shelf there are ribbon of “beach rock” and cemented estuarine sand, formed by freshwater outflow from the beach face or the estuary. The freshwater outflow, charged with $CaCO_3$ cements the coastal sediments along the freshwater/seawater interface, and marine erosion resulting in coastal retreat exposed the cemented sand. Rapid retreat during storm, where tens of metres of coast mat retreat within a day, leaves behind a ribbon of cemented sand which is left stranded offshore. Successive storms over thousands of years leaves behind parallel strips of such cemented material as shore-parallel ribbons (Semeniuk & Searle 1986).

Progressive coastal retreat of the barrier dune that is sheltering and barring an estuarine lagoon, exposes at the submarine “toe” of the barrier the sheet of estuarine sediment (Semeniuk 1980). This is often exposed as a small cliff cut into estuarine mud that forms a distinctive small scale unit along the submarine edge of the barrier.

Storms transport material from the inner shelf onto the shore face, and as such, the beach may be littered by marine shelf shells, limestone lithoclasts, and “sea biscuits”.

6.4 Stratigraphy

While the stratigraphy has been indirectly and directly described in the sections above, for completeness, the stratigraphy of the Study Area is systematically described in this section in formal terms, chronologically, lithologically, and in terms of inter-relationships.

The stratigraphy in the region is described from the oldest unit to the youngest unit.

There are ten stratigraphic units identified at formational level in the region. Many of the Holocene formational units are diachronous, *i.e.*, they are not deposited at the one time interval and cross time boundaries. As such, they may be equivalent in age to a number of adjoining units. Note that the sediments filling the large wetland basins in the region, apart from the Leschenault Formation filling Leschenault Inlet Estuary, are as yet not formally described and named. The stratigraphic units that are formally identified, named, and described in Table 1 below, from youngest to oldest, are:

Safety Bay Sand
Preston Beach Coquina
Leschenault Formation
Kooallup Limestone
Myalup Sand
Tims Thicket Limestone
Eaton Sand
Bassendean Sand
"Tamala Limestone"
Pleistocene shelly limestone (un-named)

The stratigraphic units generally are younging towards the west, with the Bassendean Sand and the Eaton Sand occurring to the far east. The next units that were deposits probably were the ridges of aeolian sediments that lithified to become aeolianite ridges (the Garden Island Ridge, the Five Fathom Bank ridge that is expressed as the Bouvard Reefs, and the Buffalo Reefs in the south of the Study Area). On the Yalgorup Plain and the belt of sediment involving the Quindalup Dunes, the sediments definitively form a "younging-westwards" sequence, with fillets and ribbons of sediments abutting each other as the overall sedimentary pile accreted westwards, from Tims Thicket Limestone, to Myalup Sands, to Kooallup Limestone, to the Holocene formations.

A summary of the stratigraphy of the Pleistocene formations and their relationship the Holocene barrier dune is shown in Figure 12.

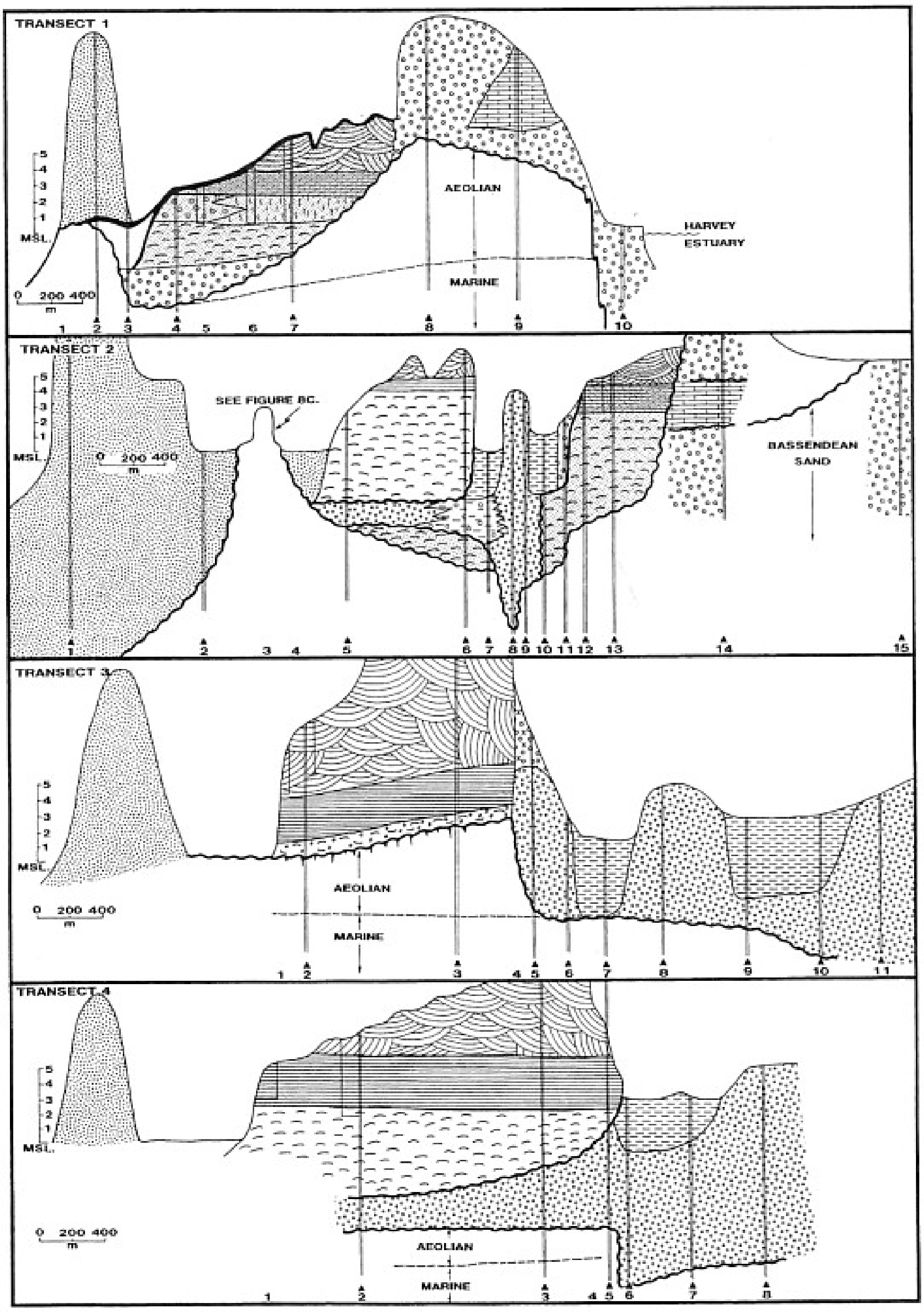

Figure 12: The lithological sequence and stratigraphy of Pleistocene units across the Yalgorup Plain (see Semeniuk 1996 for more stratigraphic details).

In Figure 12, in all transects, the white area under the lowermost unconformity is undifferentiated Pleistocene shelly limestone. In all transects, the high-relief sand body perched on undifferentiated Pleistocene shelly limestone is the Holocene sand of the Leschenault-Preston Barrier. In Transects 1 & 4, the easternmost sand body is the Eaton Sand of the Mandurah-Eaton Ridge. Transect 1 is dominated by the three facies of the Tims Thicket Limestone, and Transect 4 is dominated by the three facies of the Kooallup Limestone. Transect 2 comprises, from east to west, Eaton Sand, Tims Thicket Limestone, Myalup Sand, Kooallup Limestone, and Holocene sand. Transect 3 is dominated by Kooallup Limestone, and to the east, a ridge of Myalup Sand and then Eaton Sand.

Details of the seagrass bank, beach, and dune stratigraphy of the Kooallup Limestone and the Tims Thicket Limestone is shown in Figure 12. The rocky shore of the Pleistocene limestone reef that influenced cuspate foreland sedimentation during accumulation of Tims Thicket Limestone is also shown in Figure 13.

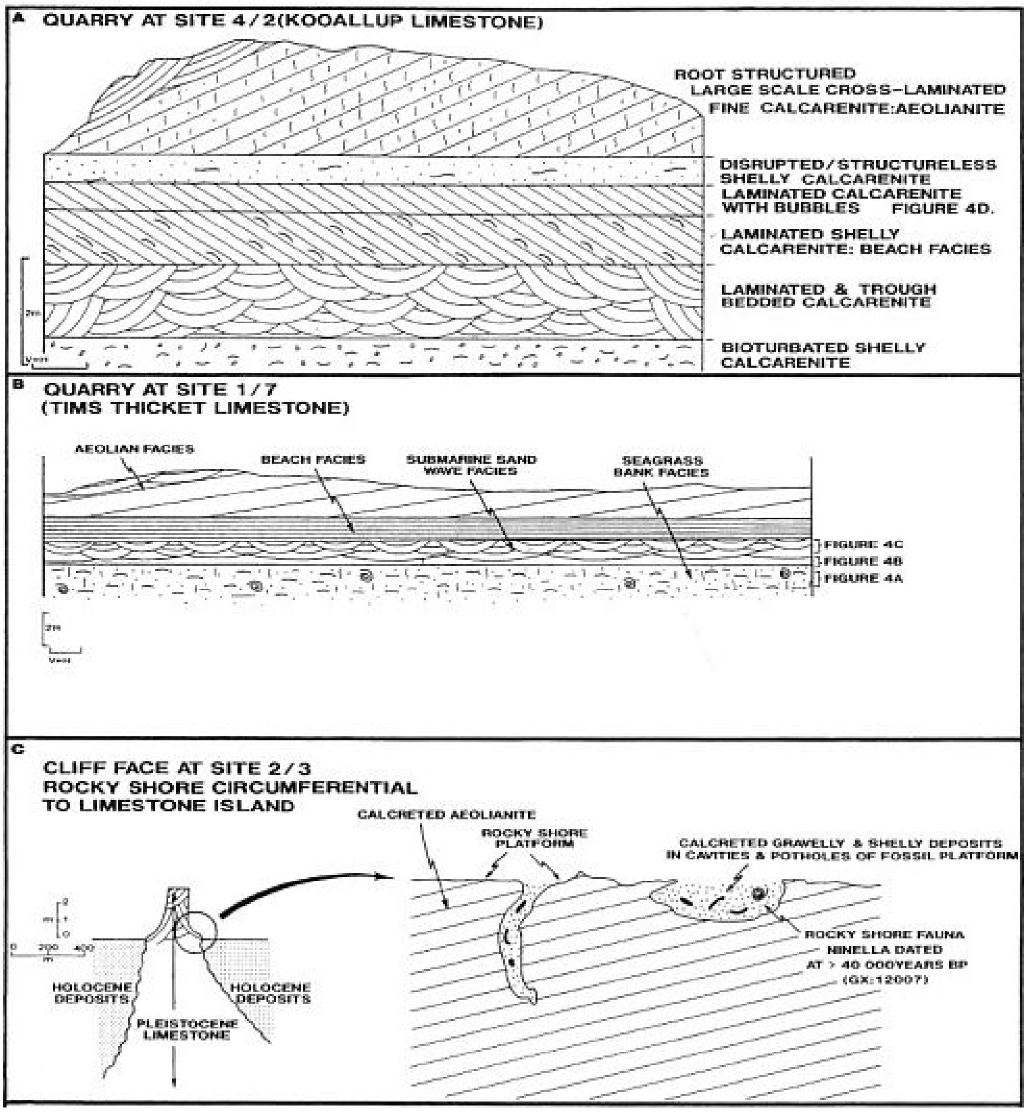

Figure 13: Details of the stratigraphy of the Kooallup Limestone and the Tims Thicket Limestone showing the three facies in vertical sequence (seagrass bank sediment, beach sediments, and dune/beachridge sediments), and the rocky shore sequence.

The palaeo-geomorphology of the Tims Thicket Limestone and Kooallup Limestone showing overall cuspate foreland form of the deposits and the beach ridge trends therein is illustrated in Figure 14 (Semeniuk 1997). Figure 15 shows the same patterns of beach ridges from Figure 14, but with the modern patterns from the Point Becher cuspate foreland (C A Semeniuk 2007) superimposed to show the correlation and similarity between Pleistocene and Holocene geomorphology and beachridge patterns.

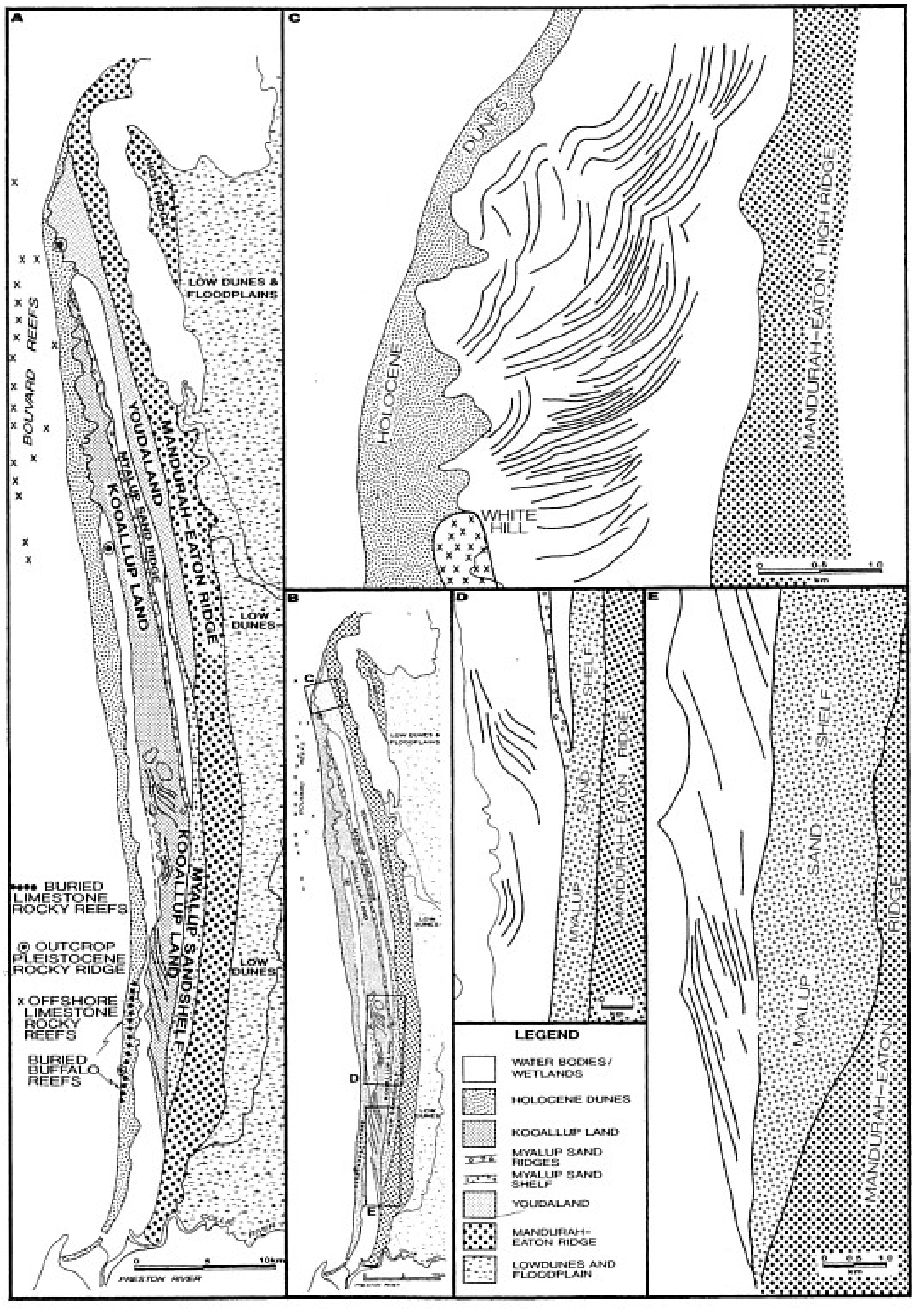

Figure 14: Geomorphology and beachridge patterns of the Tims Thicket Limestone and Kooallup Limestone (after Semeniuk 1997).

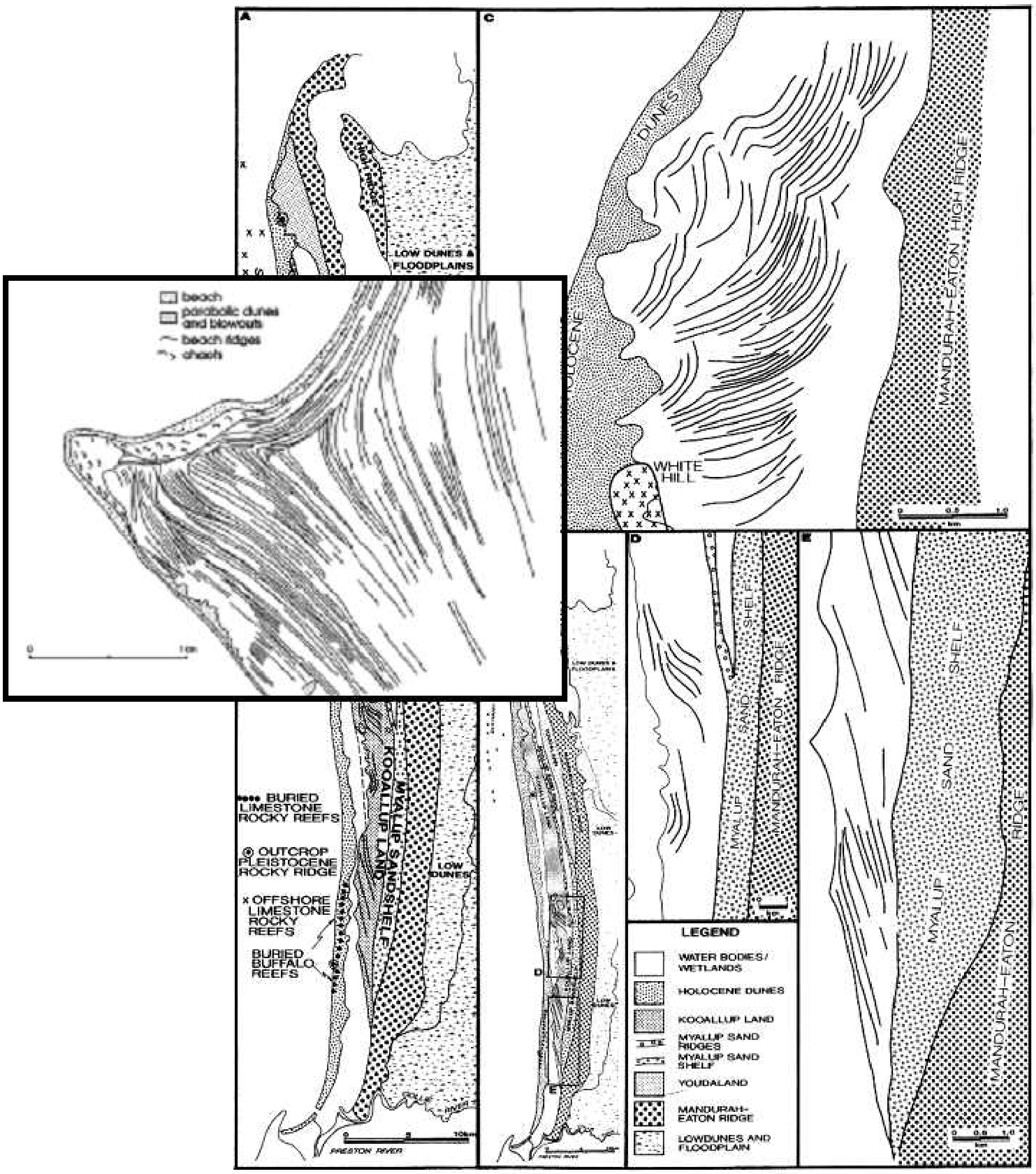

Figure 15: Geomorphology and beachridge patterns of the Tims Thicket Limestone and Kooallup Limestone with modern patterns from Point Becher superimposed (after Semeniuk 1997 and C A Semeniuk 2007).

Table 1: Stratigraphic units in the Study Area

Youngest units			
Formation	**Age**	**Lithology**	**Stratigraphy and relationships**
Safety Bay Sand	Holocene	mainly fine to medium calcareous and quartz sand	cross-laminated to structureless sand sheets and wedges, intercalated with humic soils, and marked internally with erosional disconformities; lithologically transgressive calcrete at depth; the formation conformably rests on and interfingers with Leschenault Formation, conformably rest on Preston Beach Coquina, and unconformably rests on Kooallup Limestone and Tims Thicket Limestone
Preston Beach Coquina	Holocene	mainly shell gravel and sandy shell gravel	intercalated shell gravel and sandy shell gravel that rests conformably on Leschenault Formation, and is overlain conformably by Safety Bay Sand
Leschenault Formation	Holocene	estuarine mud, shelly mud, sand, shelly sand, and muddy sand	intercalated mud, shelly mud, sand, shelly sand, and muddy sand unconformably resting on Kooallup Limestone and Tims Thicket Limestone, and conformably overlain by Preston Beach Coquina and Safety Bay Sand
Kooallup Limestone	Youngest Pleistocene limestone unit in area	fine grained calcarenitic aeolianite, laminated calcarenite and shelly calcarenite, bioturbated shelly calcarenite,	fine grained calcarenitic aeolianite overlying laminated calcarenite and shelly calcarenite overlying bioturbated shelly calcarenite, representing upward shoaling sequence from seagrass sedimentation to beach sedimentation to coastal dunes; unconformably overlying Myalup Sand, and unconformably overlain by Safety Bay Sand
Myalup Sand	Pleistocene	fine to medium grained quartz sand; shelly at depth	ridge and ribbon of sand unconformably overlain by Kooallup Limestone and unconformably overlying Tims Thicket Limestone
Tims Thicket Limestone	Pleistocene	fine grained calcarenitic aeolianite, laminated calcarenite and shelly calcarenite, bioturbated shelly calcarenite,	fine grained calcarenitic aeolianite overlying laminated calcarenite and shelly calcarenite overlying bioturbated shelly calcarenite, representing upward shoaling sequence from seagrass sedimentation to beach sedimentation to coastal dunes; unconformably overlying and abutting Eaton Sand and un-named Pleistocene shelly limestone sheet, and unconformably overlain by Myalup Sand and Safety Bay Sand

Eaton Sand	Pleistocene	fine and medium grained quartz sand, and local calcarenite aeolianite lenses	ridge of fine and medium grained quartz sand with embedded calcarenitic aeolianite lenses, unconformably abuts and overlies Bassendean Sand
Bassendean Sand	Pleistocene	fine and medium grained quartz sand	sheet of fine and medium grained quartz sand: unconformably abutted and overlain by Eaton Sand, and unconformably overlying un-named Pleistocene shelly limestone
"Tamala Limestone"	Pleistocene limestone in the Study Area	aeolian calcarenite	aeolian calcarenite forming ridges in the marine environment (specifically the Bouvard Reefs, and the Buffalo Reefs of Semeniuk 1995, 1996)
Pleistocene shelly limestone (un-named)	oldest Pleistocene limestone in the Study Area	calcarenite and shelly calcarenite	calcarenite and shelly calcarenite that is unconformably overlain by a variety of Pleistocene units
Oldest units			

6.5 Hydrology

The stratigraphic units in the Study Area, and the interfaces between them form hydrological units, or functions as specific hydrological interfaces.

The main hydrological settings in the Yalgorup Plain area are as follows:

The Eaton Sand that underlies the Mandurah-Eaton Ridge is recharged by rain and stores freshwater. It discharges the freshwater along the contact between the Mandurah-Eaton Ridge and the Tims Thicket Limestone.

The Tims Thicket Limestone is recharged by rain through the porous limestone and through pipes and karst features, and stores freshwater. Flow through the limestone aquifer is variable depending on the occurrence of calcrete sheets, and the grainsize and extent of cementation of the calcarenites (aeolianites versus beach calcarenites versus shelly fine grained calcarenites formed in former sea grass bank environments). It discharges the freshwater towards the Myalup Sand and along the shore of Lake Clifton.

The Myalup Sand is recharged directly by rain through its porous sand surface, and receives water from the adjoining Tims Thicket Limestone aquifer. Water is stored in this sandy aquifer. Flow through the sand aquifer is towards the Kooallup Limestone, where it meets a relatively less permeable aquifer, with hydrological complications occurring along this interface.

The Kooallup Limestone is recharged by rain through the porous limestone and through pipes and karst features, and stores freshwater. The limestone also receives fresh water sourced from the Myalup Sand aquifer. As with the Tims Thicket Limestone, flow through the Kooallup Limestone aquifer is variable depending on the occurrence of calcrete sheets, and the grainsize and extent of cementation of the calcarenites (aeolianites versus beach calcarenites versus shelly fine grained calcarenites formed in former sea grass bank environments). The aquifer discharges the freshwater towards the west into Lake Preston.

The Leschenault-Preston Barrier is recharged by rain through the porous sand, and stores freshwater in a mound. Flow through the aquifer is variable depending on the occurrence of aeolian sand, shelly sand, shell gravel, soil sheets, calcrete sheets, and the grainsize and extent of cementation of the sand. The aquifer discharges the freshwater towards the east into Lake Preston and to the west into the Indian Ocean.

The Leschenault-Preston Barrier hydrology has been studied in some detail in the Leschenault Peninsula area, and much of the patterns derived from there can be applied to the Barrier in the Study area. In the Leschenault Peninsula area, meteoric water recharges the groundwater under the barrier, forming a mound (Figure 16). This groundwater discharges by seepage to the sea, and to the estuary, and is discharged by transpiration by the vegetation especially along its eastern margin, and especially by the tuart stands (Semeniuk & Meagher 1981b). Major zones of freshwater seepage are noted along the contact of the barrier with the estuary (Cresswell 2000), a factor that sustains specific assemblages of peripheral vegetation. The patterns derived from the Leschenault Peninsula area can be applied to the Study Area, with the caveat that the stratigraphy in the central to northern Leschenault-Preston Barrier is stratigraphically more complex, and hence the hydrology can be expected to be more complex, especially in the seepage Lake Preston.

The patterns of hydrology under and freshwater seepage from the Leschenault Peninsula is shown in Figures 16 & 18.

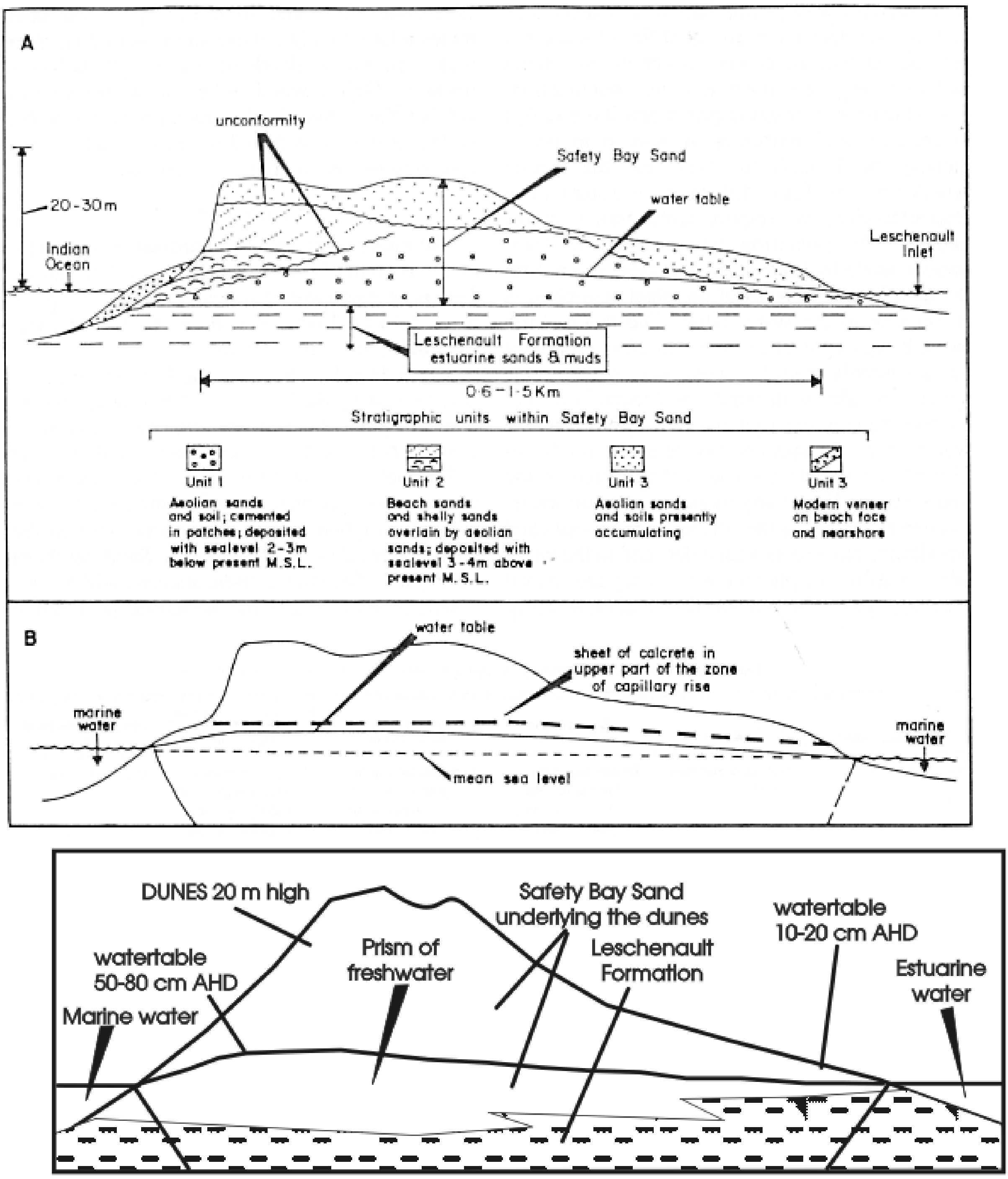

Figure 16: A. Generalised stratigraphy of the Leschenault Peninsula showing stratigraphic units and the position of the water table (Semeniuk & Meagher 1981b). B. Position of water table under the Leschenault Peninsula, and the occurrence of calcrete as a sheet just above the water table C. Generalised hydrology of the Leschenault Peninsula showing prism of freshwater, and its relationship to the stratigraphic units. A zone of freshwater seepage will occur to the sea and to the estuary, the latter located along the sand/mud interface.

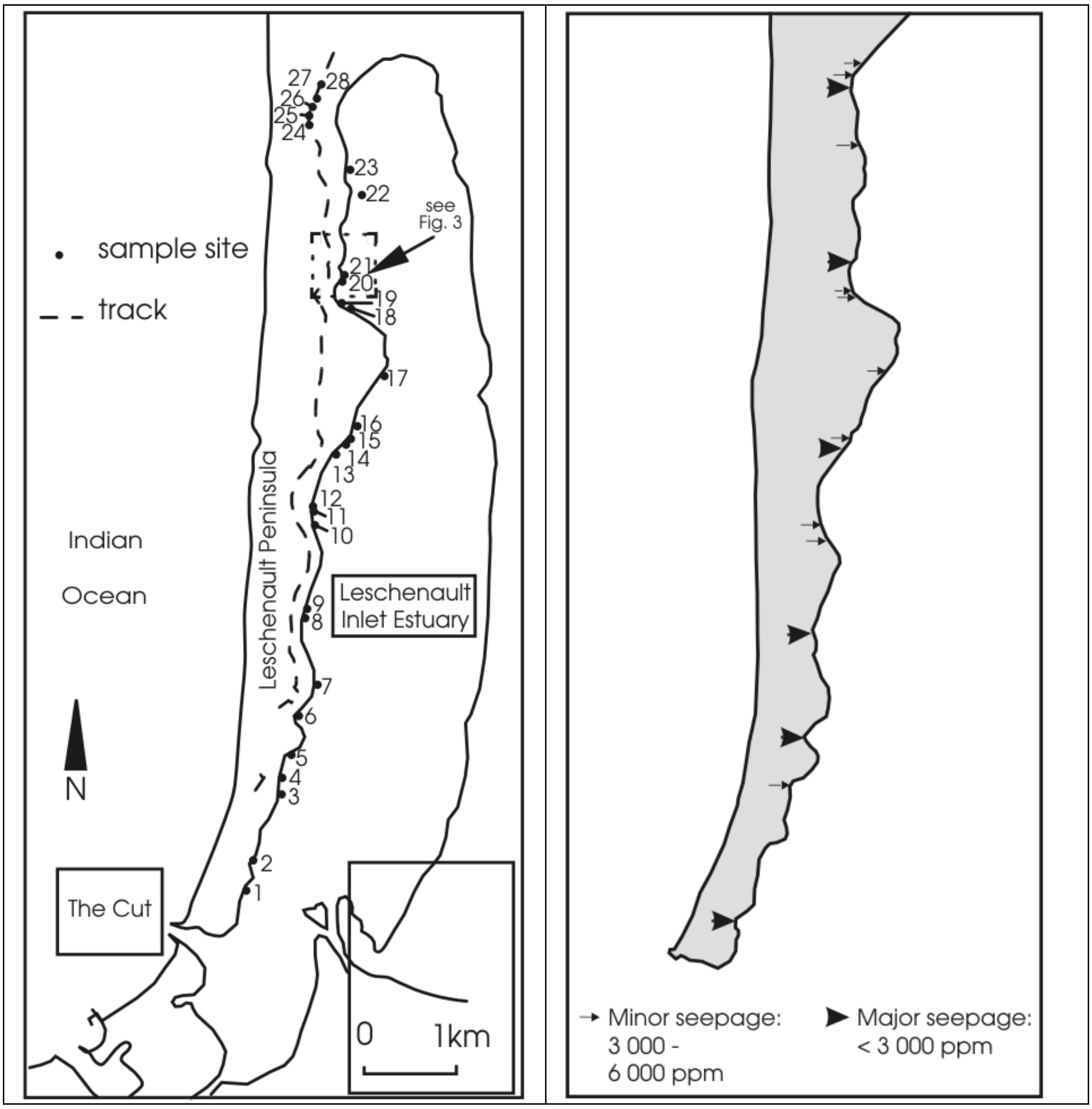

Figure 17: Zones of freshwater seepage from the Leschenault Peninsula into the estuary of Leschenault Inlet (after Cresswell 2000). To left, the sampling sites. To right, the main points of seepage localised in conduits.

Apart from the storage and internal flow that is influenced by the specific stratigraphic formations and their range of lithology, other important stratigraphic interfaces and lithologies that influence lateral and downwards flow and discharge in the system are the occurrences of calcrete sheets that as relatively impervious sheets can act as aquatards and divert water flow, mud and muddy sand of the Leschenault Formation that similarly act as aquatards and divert water flow especially along its contact with overlying sandy formations, and shelly layers that accelerate or direct water flow.

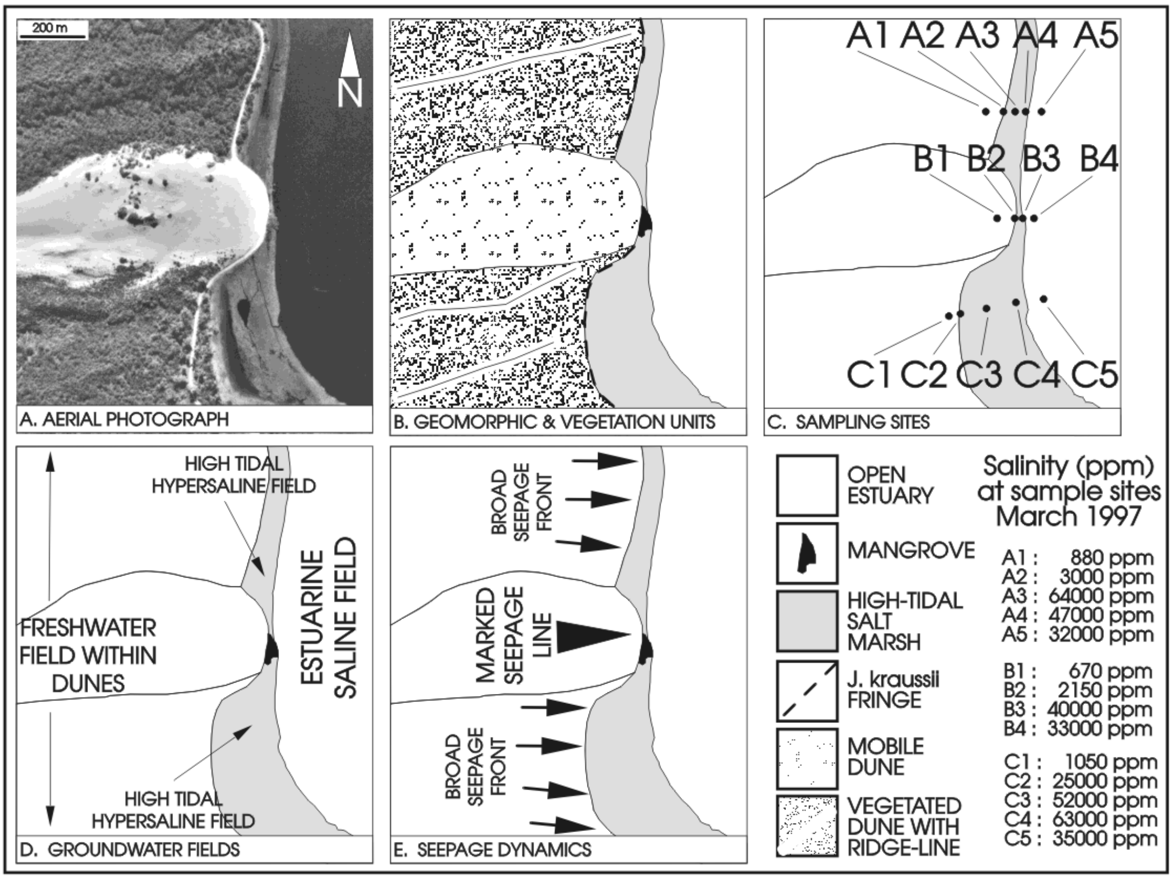

Figure 18: Freshwater seepage from the Leschenault Peninsula into the estuary of Leschenault Inlet (after Cresswell 2000) along a finger of dune sand, showing seepage localised in a specific aquifer (conduit).

6.6 Karst

Karst is a largely unexplored feature of the Yalgorup Plain region. The Speleological Society of Western Australia does not record caves and speleothems in the region and the area is not known for caving activities. However, there are numerous karst features in the Study Area expressed at various scales.

Karst is a term applied to the special landforms, features and drainage resulting from greater solubility of certain rocks in natural waters. Karst topography for instance is a landscape shaped by the dissolution of a layer or layers of soluble bedrock, usually carbonate rock such as limestone or dolomite. In karst terrains, due to subterranean drainage, there may be very limited surface water, to the extent that there is an absence of rivers and lakes. Many karst regions display distinctive surface features, with sinkholes or dolines being the most common. However, distinctive karst surface features may be absent where the soluble rock is mantled by youger soils and other sedimentary deposits, or overlain by non-soluble rock strata. Some karst regions globally include thousands of caves, even though evidence of large caves is not a required characteristic of karst.

An important characteristic of karst is scale. Karst features can range in scale from large subterranean caverns and underground channel systems, to small caves, small cavies and fissures.

There are a range of karst features in the Yalgorup Plain area ranging in scope and scale. There range from large dolines, to linear solution features, to pipes, to solution fissures.

The most common expression of karst is the solution fissures and pipes in the Pleistocene limestones. Solution fissures are small scale features evident along bedding planes and in vertical to sub-vertical fractures traversing the limestone. They are millimetres to a centimetre in width, and may extend discontinuously through the limestone. They increase the transmissivity of the limestone aquifers and providing preferred pathways for water. Pipes are the cylindrical punctures that vertically traverse the limestone. They are usually ~ 10 cm to 30 cm in diameter, roughly circular, and often filled with quartz sand. They have been termed "solution pipes" elsewhere on the Swan Coastal Plain. These pipes are commonly lined with a millimetre to centimetre crust of laminated calcrete. Their hydrological function is the rapid transfer of meteoric waters to the subsurface.

Another expression of karst is the doline that has been developed on the Kooallup Limestone. In the southern part of the Yalgorup Plain, there is a circular doline, several metres deep, that probably developed during a Pleistocene sea level low-stand during a glacial period. With a rise in sea level and a rise in the water table, the doline intersected the water table, and has since been filled with wetland sediments.

A linear and ubiquitous expression of karst is developed along the interface of the Myalup Sand and Kooallup Limestone. As described earlier, the Myalup Sand rapidly and efficiently receives and stores rainwater, and discharges it westwards towards the Kooallup Limestone. The Limestone, being less transmissive, temporarily "bars" the throughflow, and along the contact of the Myalup Sand and Kooallup Limestone there is solution of the Kooallup Limestone, with its slow and progressive retreat as a "cliff line" westwards, resulting in the westward expansion of the linear wetlands developed along this interface.

6.7 Wetlands

Wetlands are a common feature of the Study Area. They can be divided into seven groups that are internally variable and interrelated both in type and spatially. From east to west, that is, from oldest landscape to youngest landscape, the wetland types are:

1. The Lake Clifton Chain of wetlands
2. The Myalup Sand Shelf Chain of wetlands
3. The Martins Tank Chain of wetlands
4. The Lake Preston Chain of wetlands
5. Palaeo-wetlands on the Youdaland terrain
6. Doline on the Kooallupland terrain
7. Perched wetlands on the modern surface of Kooallupland terrain

The Lake Clifton Chain of wetlands occurs along the interface between the Mandurah-Eaton Ridge and the Tims Thicket Limestone. Probably it was initiated as a lagoonal depression behind the barrier of the Myalup Sand ridge (similar to the modern Coorong and Leschenault Inlet to lake Preston depressions behind the Younghusband Peninsula and Leschenault Peninsula). Stratigraphic information (held in-house by the V & C Semeniuk Research Group as part of its R&D endeavour; Semeniuk & Semeniuk in preparation) shows that this linear depression has had a complex Quaternary sedimentary history. At present, it functions as a linear lake in its northern part, and along its length changes to sumplands, and to damplands. Sedimentary fill in this chain is complex, ranging from carbonate muds, shelly carbonate muds, sand, and shelly sand (Coshell & Rosen 1994; C A Semeniuk 1988; Semeniuk 1997). To the south in the area of the Myalup

Sand Shelf, it is floored by sandy wetland deposits. The eastern margin of the northern part of the Lake Clifton Chain of wetlands, and specifically along the eastern shore of Lake Clifton (*sensu stricto*), where groundwater charged with $CaCO_3$ from the Tims Thicket Limestone enters the lake, there is development of shore-parallel wedge of stromatolite heads and sheets (also termed "thrombolites" by some authors).

To the south, the Myalup Sand Ridge loses its ridge character and becomes a broad shelf adjoining the Mandurah-Eaton Ridge. In the past, at the time of its formation, it would have been a shore-parallel shelf of sand that prograded from the Mandurah-Eaton Ridge and there probably would have been low-key development of low relief beach ridges. This is the setting for the development of wetlands that comprise the Myalup Sand Shelf Chain of wetlands. These wetlands are sand – floored and locally peat-filled to shallow depths.

The Martins Tank Chain of wetlands occurs between the Myalup Sand Ridge and the Kooallupland. It is developed as a series of wetlands, ranging in type from lakes to sumplands to damplands, along the edge of the Kooallup Limestone, where discharge of groundwater from the Myalup Sand aquifer is "barred" by the less transmissive Kooallup Limestone. In principle it is similar to the chain of wetlands on the central Swan Coastal Plain where the Bassendean Dunes interface s with the limestones of the Spearwood Dunes and forms a chain of wetlands such as North lake, Bibra Lake and Thompson Lake.

The Lake Preston Chain of wetlands is a complex system. Formerly, as a linear lagoon and estuarine lagoon it was barred by the Leschenault-Preston Barrier, with deltas to the extreme south of the lagoon. With eastward retreat of the Barrier, the central part of the lagoon was partitioned into a (northern) Lake Preston, and a (southern) Leschenault Inlet. Lake Preston itself, and the stranded northern part of Leschenault Inlet are in the Study Area. As such, the Lake Preston Chain of wetlands consists of Lake Preston (which functions now as a lake or lagoon), a series of isolated sumplands and damplands as a southern extension of Lake Preston, and the prograded and stranded mud flats of the northern part of Leschenault Inlet. Sediments in the wetlands range from being sandy and shelly (where distant from the fluvial input), to muddy and shelly mud where proximal to the fluvial input (*viz*., Leschenault Inlet).

As noted earlier, on modern beach ridge plains as at Point Becher, wetlands are developed as primary slacks, formed by spits that bar a portion of the sea isolating them as lagoons, dune slacks, or lakes from the main ocean, and can form with groundwater table rise in swales of beach ridges (C A Semeniuk 2007). Youdaland has formed as a beach ridge complex (Semeniuk 1997), and in this context, there are palaeo-wetlands on the Youdaland terrain formed similarly to that on the modern Point Becher beach ridge plain. They were filled partially with carbonate mud that has since been calcrete impregnated. While formed in the Pleistocene, with their elevated water tables relative to modern water tables, these palaeo-wetlands are not intersecting the modern water table, but continue to act as wetlands in that they perch meteoric water by their calcrete-impregnated wetlands sediments.

A rounded doline occurs on the limestone terrain of Kooallupland. While Pleistocene in age as a geomorphic feature, and probably developed during the glacial period when sea levels were at a low-stand, this doline has filled with Holocene wetland sediments.

The calcreted modern surface of Kooallupland terrain acts to perch rainwater, and has developed perched wetlands. These are referred to the Kooallup Suite by C A Semeniuk (1988). These wetlands are localised to the south of Kooallupland, and are shallowly filled with carbonate mud and shelly carbonate mud.

With all the wetlands described above, the peripheral vegetated zones are considered to be part of the wetland, but an important ecological part of each wetland.

The wetlands in the Study Area, particularly the linear lakes, where they are mud-filled or mud-lined, tend to perch water, or at least retard groundwater through-flow and, as such, over the millenia, have salinized. As a result, the hydrologic functioning, and hydrochemistry, of many of the wetland basins in the Study Area are saline water bodies. These saline water bodies are embedded in a groundwater system, albeit residing in different types of aquifers, of a generally freshwater nature or hyposaline water nature.

6.8 Sea level history

The late Quaternary of the Study Area has had a variable sea level history, which has been instrumental in developing the various packets of stratigraphic units and developing the stratigraphic units at various heights above modern sea level, with their implications for hydrological functioning and hydrological interactions.

The sea level history is separated into four episodes from Pleistocene to Holocene.

The Tims Thicket episode, with progradation of carbonate sediments at a sea level initially at 4.5 m above its modern present level, falling with progradation to 3 m above its modern present level.

The Myalup episode, with sea level at 2-3 m below its modern present level.

The Kooallup episode, with progradation of carbonate sediments at a sea level 3.0 m above its modern present level.

The Holocene episode, with sea level 6 m below its present position and progradation of a cuspate foreland in the Bouvard Reefs area some 8000 years ago, with sea level 2 m below its modern present level and formation of the Leschenault-Preston Barrier some 7500 years ago, with sea level 3-4 m above its present level and progradation of sand and shelly sand about 5000-45000 years ago, and since then with sea level falling to its present position.

7.0 Key Quaternary features

There are seven key features in the Quaternary landscape and geology of the Study Area; these are:

1. Pleistocene stratigraphy, landforms and history
2. south to north style of the Holocene barrier dune
3. Holocene barrier history
4. wetlands
5. record of a rising sea level in a bathymetrically complex coast
6. stratigraphy linked to hydrology
7. stromatolites/thrombolites

The Pleistocene stratigraphy, landforms and history are a key feature of the Study Area. They have no counterpart on the Swan Coastal Plain elsewhere. The ensemble of Pleistocene landforms, with intervening wetlands, and the clear stratigraphy related to former sea levels are unique to this area in Western Australia. North of Shark Bay, and along the tropical Western Australian Coast (in the Pilbara region, along the Canning Coast and along the Kimberley; (Semeniuk 1993, 1995, 2008), the sedimentary style with its macrotides, and tidal flat dominated sedimentation is completely different and hence incomparable to what occurs along the Yalgorup Plain. The Shark Bay region also is wholly different to the sedimentary style and type of preservation. Moreover, the Shark Bay region does not preserve the Pleistocene sequences well, as they are only in scattered outcrops. The central and north Swan Coast Plain, though with exposures of Pleistocene limestone, does not show the stratigraphic sequence and development of landscape and land types so evident in the Yalgorup Plain region. The central and north Swan Coast Plain essentially is depauperate in the preservation of Pleistocene marine limestones and landforms, and Pleistocene limestones are only present in scattered outcrops and in exposures along the sea cliffs of the Perth Coast.

The Yalgorup Plain thus represents the best preserved sequence of Pleistocene landforms derived from coastal sedimentation in Western Australia, and clearly the best preserved series of marine prograded Pleistocene limestone system in Western Australia. Moreover, there is no equivalent of the sequence of prograding accreting limestone of various Pleistocene ages as manifest on the Yalgorup Plain elsewhere in Australia. The nearest neighbour is the Coorong area, where the Pleistocene Bridgewater Formation (a Pleistocene limestone), forms a prograded limestone coastal plain comprised of beach ridge, but here there is only one phase of Pleistocene history, with Pleistocene limestone fronted by a Holocene barrier (*i.e.*, the Bridgewater Formation, abutted to seaward by the Holocene dune barrier), and not the Pleistocene sequence of Eaton sand, Tims Thicket Limestone, Myalup Sand, Kooallup Limestone, and the Holocene dune barrier).

Barriers are normally fairly homogeneous along their length, since most are embedded wholly with the same climatic setting, and generally do not cross a tectonic gradient. The barrier of the Younghusband Peninsula in South Australia, for instance, is approximately east-west in orientation, and the barriers across the estuaries along the southern coast of Western Australia also are mostly approximately east-west in orientation.

The Leschenault-Preston Barrier crosses ~ 50 km of a latitudinal gradient, crosses from a barrier-free coast to a region where offshore reefs begin to influence coast forms, and crosses a tectonic gradient. As such, the Leschenault-Preston Barrier shows changes in barrier style and dune styles and landforms from south to north, and marked changes in Holocene stratigraphy from south to north. This generally is not a feature documented elsewhere nationally or globally for barriers dunes, and is a feature of significance.

Further to this, the south to north variability has resulted in a complex barrier history at a given site and axiomatically a variable barrier history from south to north. This also generally is not a feature documented elsewhere nationally or globally, and is a feature of significance.

The wetlands in the Yalgorup Plain area are unusual and unique. They are linked to the evolution of the Pleistocene landforms, to stratigraphy, to interfaces between stratigraphic units, to the height (or elevation) of the Pleistocene landforms, and represent along the Yalgorup Plain various types of wetland formation transcending Pleistocene origins to Holocene origins, with Pleistocene developed forms persisting into the Holocene. They represent a nationally and globally distinct and unique suite of wetlands that are text-book classic examples of both styles of wetland evolution and variability of wetlands development linked to landscape development and hydrology.

One of the most significant features of the Study Area is that the northern part is located at the junction between coastal sectors II and III of Searle & Semeniuk (1985), a junction where the offshore ridges of limestone, so prominent in the Rockingham to Dongara area, intersect the main coast and are buried below Quaternary deposits. As such, the Bouvard Reef area is the last location where offshore reefs play a prominent part in coastal development and coastal sedimentation. Semeniuk (1995) described the stratigraphic record of a post-glacial Holocene sea rising into a bathymetrically complex coast (where the Bouvard Reefs were extant), and showed the complexities that can occur with a rising sea level when inundation is in such a bathymetrically complex zone. Thus, this sector of coast, and its stratigraphy stands as a global model for coastal response to rising sea levels, and will be an important area for modelling and understanding coastal response to predicted rising sea levels due to global atmospheric and sea temperature warming.

The Yalgorup Plain, the Mandurah-Eaton Ridge, and the complexity of the Holocene barrier, provides a terrain wherein it is evident that stratigraphy is linked to hydrology. This is because the stratigraphic units are clearly separated by distinct lithology or stratigraphic units are at distinct topographic levels (*e.g.*, the quartz sand ridge of the Myalup Sand distinctly and sharply adjoins the Tims Thicket Limestone and the Kooallup Limestone, and separates the two limestone formations, which themselves occur at two different topographic levels). The Study Area thus provides a classroom of hydrology and hydrogeology of geoheritage significance (see later). Also, the consequences the relationship that stratigraphy is linked to hydrology is that there are definitive ecological communities linked to the hydrology and hydrochemistry as linked to hydrology and stratigraphy. Also, wetlands that are saline water bodies, perched on and embedded in a generally freshwater groundwater system, provide local recharge of saline water in the groundwater system.

Stromatolites (or thrombolites) occur only rarely in inland lake systems. They have been documented in the Eyre Peninsula, but not commonly documented elsewhere around the world. In Western Australia, similar structures occur along the shore of Lake Richmond, and Lake Thetis, and as fossil forms along the eastern shore of Lake Walyungup.

Most stromatolites, or algal mats, occur in hypersaline tidal flat environments (*e.g.*, Shark Bay, or western Persian Gulf), and so those along the shores of inland lakes assume International significance.

The stromatolites (or thrombolites) of the Lake Clifton system are domal and linked domal structures. They are up to 50 cm high and 30 cm diameter, expanding in diameter from the base of the dome upwards. Internally they are crudely layered, with thin layer-parallel laminoid cavities and amoeboidal to equant cavities. The layers are composed of micro-laminated pelleted and micritic carbonate and clotted micritic carbonate.

The stromatolites (or thrombolites) of the Lake Clifton system are specifically important in that they only occur along the eastern shore of lake Clifton, where the lake interface s with the aquifer of the Tims Thicket Limestone, and $CaCO_3$-enriched groundwater seeps from the aquifer onto the shore. The stromatolites form an westward thickening wedge. The accumulation and individual stromatolite heads are particularly important in that they are planed (or horizontally truncated) along their shoreline edge, indicating that they had formed in times of earlier and higher water levels, and have since been planed to levels of the modern high-water stand. These stromatolites hold an invaluable record of water chemistry and climate history in their internal structures and micro-stratigraphy.

8.0 National and International comparisons

Prior to undertaking National and International comparisons, some background information is provided here as to the rationale for such comparisons.

To assess the significance of a geological feature, it has to be viewed in an International to local perspective, and in the case of the Yalgorup Plain and Study Area, it involves comparing the coastal types and coastal plain features, in the first instance, within the same climatic setting, and in the second instance, to the same global scale coastal category.

In the first instance, coasts around the world, and their associated coastal plains, occur in distinct climate belts, and the coast processes and coasts plains are linked to these climate setting. Thus, the subtropical subhumid to semiarid south-western Australia coast and coastal plain should not be compared to boreal and temperate coast, or even to tropical coasts. In this context, the appropriate coasts for comparison for the Study Area occur in the climate belt labelled “C” in Figure 19.

The south-western Australia is located in climate belt “C”, equivalent to the east coast of Australia, the southern tip of Africa, the east and west coast of South America, the Miami and Florida coast of eastern Northern America, the Californian coast of western Northern America, the shores of the Mediterranean region, and the east coast of China. These coasts are not limestone dominated, and limestone aeolianite dominated, being mainly fluvial coasts, estuarine coats, ria coasts, or with barriers in estuarine settings. The nearest equivalent is the northern African coast, but where limestone occurs along this coast, it does not portray the lithology, stratigraphic sequence, or history that the Quaternary of the Yalgorup Plain area exhibits. Quaternary limestone is also present in the Miami region of south-eastern Northern America, but here the limestone is oolitic. Brocx & Semeniuk (2007) show the main occurrences of Quaternary limestone globally (in Figure 31 from Brocx & Semeniuk 2007), but the limestone types noted therein are not of the stratigraphic, lithological and geohistorical character of that occurring in the Yalgorup Plain area. To date, from the literature, it appears that the sequence of limestones and the stratigraphic sequence of formations across the Yalgorup Plain is globally distinct and unique.

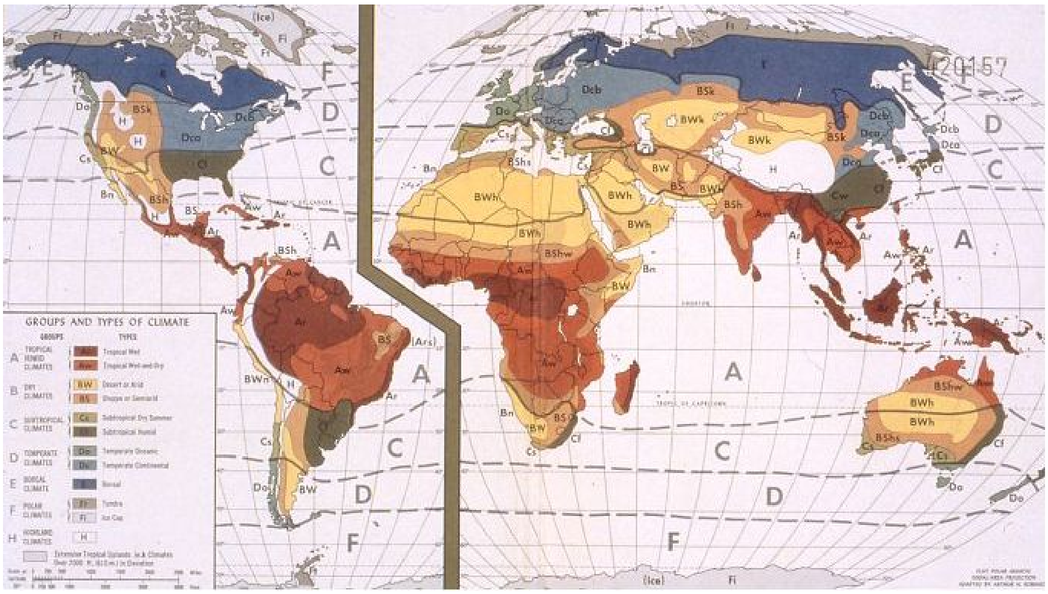

Figure 19: Climate belts around the World.

Topographically, the coasts around the world, and their associated coastal plains, are also varied, and in the first instance can be categorised, based on the model of Plate Tectonics, as Collision Coasts and Trailing Coasts. Collision Coasts carry with them features of tectonics and coastal landforms that cannot be compared to those of Trailing Coasts. Examples presented below in Figures 20-26 illustrate these principles.

The south-western coast of Australia, that includes the Study Area, is a Trailing Coast, and has been as such for tens of millions of years, and certainly as such for the Quaternary.

The western edge of the North and South American coasts are active collision coasts, with development of the Rocky Mountains chain and the Andes Mountains chain, and are incomparable to the south-western coast of Australia, that includes the Study Area. The east coasts of North and South America are Trailing Coasts, but are fluvial dominated, with development of deltas, estuaries, and barrier associated with coast retreat on estuaries.

Figure 20: North America, with tectonically uplifted western Collision Coast, and Estuary-dominated eastern Trailing Coast

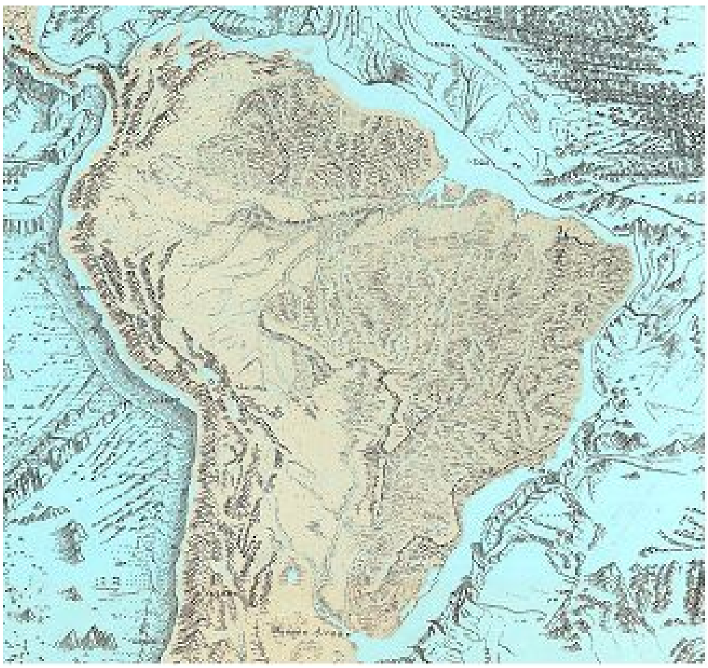

Figure 21: South America, with tectonically uplifted western Collision Coast, and fluvial and estuary-dominated eastern Trailing Coast

The European Coast, exemplified by the rocky coasts and ria coasts of Italy, Greece, Turkey, and north-western Africa are ancient, now inundated, collision coasts (Figure 22), and also cannot be compared with the Western Australian coast.

Figure 22: The northern and southern shores of the Mediterranean Sea, showing an ancient, now inundated, collision coast

The eastern South African Coast is almost comparable to the Study Area, in that it is a Trailing Coast, and essentially a "mirror image" of the Western Australian coast though on the other side of the Indian Ocean (Figure 23).

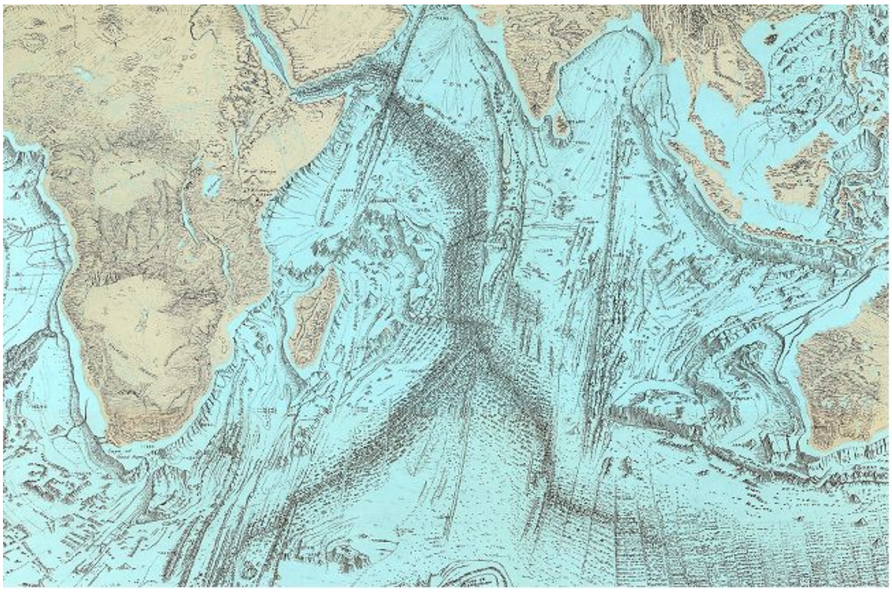

Figure 23: The Trailing Coasts of South Africa and south-western Australia, situated either side of the spreading centra of the Indian Ocean.

The eastern South African Coast, relative to Western Australia, is a latitudinally equivalent Trailing Coast. However, to the east, much of southern South Africa is bordered by barrier dunes (Tinley 1995), *e.g.*, Zululand Coast, dune barriers hundreds of kilometres long, narrow, and up to 100m high (see Figures 24 & 25). To the west, *e.g.,* in Namibia, the coast is also composed of high dunes (see Figure 26). Thus these southern African coasts are not comparable to that in the Study Area.

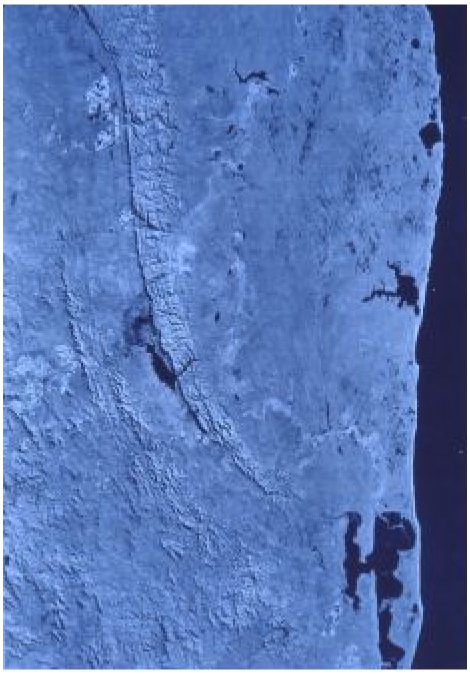

Figure 24: The eastern coast of South Africa with an extensive barrier dune along the coast.

Figure 25: Close-up of the high-relief barrier dune along eastern coast of South Africa.
(note vehicle on beach to left, for scale)

Figure 26: The sand dune dominated coastal zone of Namibia in western South Africa.

The key Quaternary features of the Study Area are compared to features similar or otherwise elsewhere.

In terms of the Pleistocene stratigraphy, landforms and history, the geomorphic and stratigraphic sequence of 1) the ridge of Eaton Sand, 2) the western ribbon of limestone, that preserves in upward shoaling stratigraphic sequence seagrass bank to beach and dune sedimentation, 3) the barrier ridge of quartz sand, and 4) the most western prograding upward shoaling sequence of limestone that preserve seagrass bank, beach and dune sediments, is at least a feature of State-wide importance, preserved nowhere else on the Swan Coastal Plain. Nor is such a sequence preserved anywhere else in Australia, rendering it a feature of National significance. But its significance may also be International, in that to date, no record of such a sequence and its implications has been published globally.

The sequence of sediments along the Yalgorup Plain records not only various sedimentary styles of accumulation in the Pleistocene, but also records a varying sea level during each inter-glacial; episode, and records a subtly differing climate and wind direction and wind intensities (*i.e.*, varying palaeo-oceanography) during each of the depositional phases during the various inter-glacial phases. As such, the sequence of the Yalgorup Plain provides an unparalleled Quaternary sedimentological, climatic, and palaeo-oceanographic record for a coastline on the eastern margin of the Indian Ocean.

While barrier development like the Leschenault-Preston system is not recorded elsewhere in Western Australia (there are barrier dune systems developed along the southern coast of Western Australia as part of estuaries but these are fundamentally different types of barriers), the south to north style of the Holocene barrier dune development in the Leschenault-Preston system, and its geomorphic variation, stratigraphic variation, and barrier history also have not been recorded elsewhere in Western Australia or Nationally. This makes the Leschenault-Preston Barrier unique at least in Australia. From the literature, the barriers documented worldwide so far are not as geomorphically, stratigraphically, or historically as complex as that of the Holocene barrier in the Study Area.

Mostly, the wetlands of the Study Area in their development, and diversity of form and origin are not described elsewhere in Western Australia, or Nationally. The exception is the estuarine lagoon and lagoon barred by the Leschenault-Preston Barrier, as such water bodies are common globally and to some extent Nationally. Estuarine lagoons and lagoons behind barrier dunes certainly are relatively common globally. Doline wetlands though common in Australia, and globally, are not so common in coastal settings. The exception to this possibly is the coastal (marine water) fed karst features in wetlands of the Eyre Peninsula in South Australia (V & C Semeniuk Research Group 2007), wherein inland lakes are fed marine waters by karst conduits, but these are not wetland dolines, but rather karst influenced water sources. Lake McLeod in central coastal Western Australia is similar - it is not a doline, but is fed by marine water through karst conduits (Logan 1987).

It appears that the wetlands of the Study area are, as an *ensemble*, unique globally because the style of development of landforms with Quaternary progradation of the limestone and quartz sand terrain appear to be globally unique. As such, globally, the wetland of the Study Area are important, and at the National level very significant.

The record of a rising sea level in a bathymetrically complex coast as described for the Bouvard Reefs area is a unique occurrence globally (Figures 27 & 28).

Because of the unique situation of the offshore reefs in proximity to the mainland shore before they descend below the coastal deposits and are buried in the Quaternary sequences, this segment of coast straddles the regions between a limestone-barrier-free coast (the Leschenault-Preston Barrier) that belongs to the Sector 2, the Leschenault-Preston Sector, of Searle & Semeniuk (1985) and a coast that is fronted and partially protected by offshore limestone ridges, islands, and reefs, *i.e.*, Sector 3, the Bouvard-Trigg Island Sector of Searle & Semeniuk (1985).

As such, with a complex rising sea level, partly influenced by tectonics, the rising sea interacted with a complex nearshore bathymetry that resulted in a mix of coastal response – at first it behaved as did Sector 3 in developing cuspate forelands in lee of the reef and ridge protection, and then with a rising sea level that nearly fully inundated the offshore reefs it behave as a limestone-barrier-free coast and developed a barrier dune as in Sector 2.

This type of coastal response appears to be unique globally, as it has not been described elsewhere, and at any rate, it provides a very important model of coastal response to a rising sea that will be useful in Western Australia and globally. As such, this site, with its stratigraphic information is a Internationally important site as a classroom for coastal studies, coastal history and a model for coastal response to potentially rising sea levels in the next decades and century.

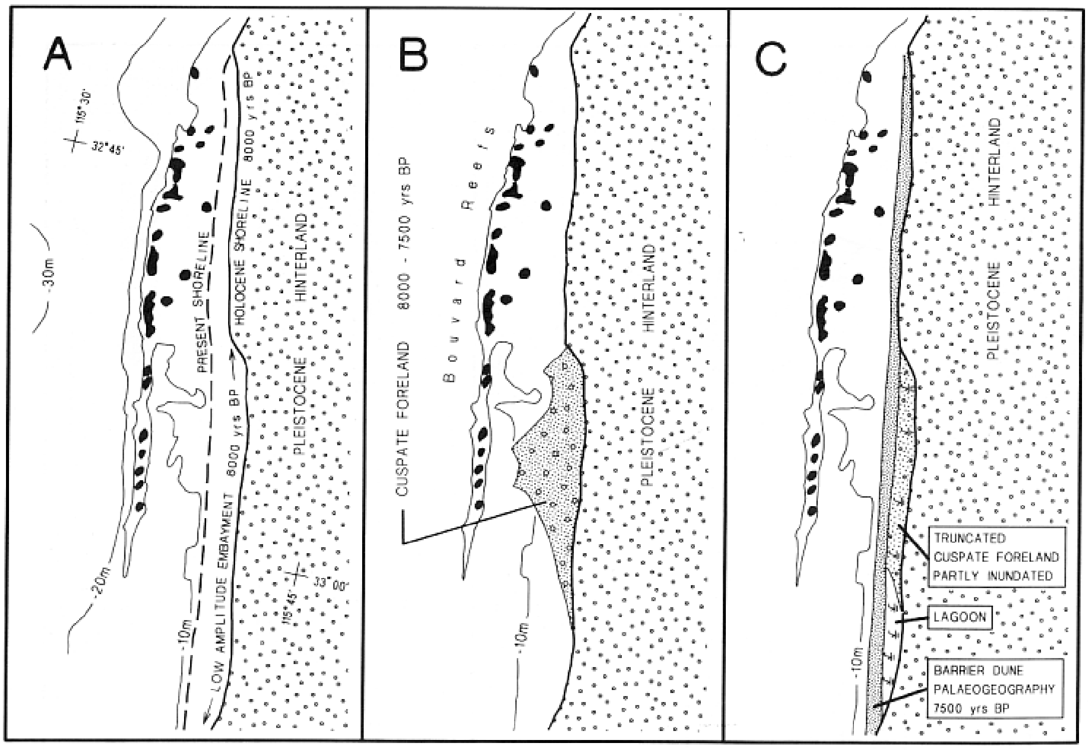

Figure 27: The evolution of the coast in the Bouvard Reefs area in plan view
(after Semeniuk 1996)

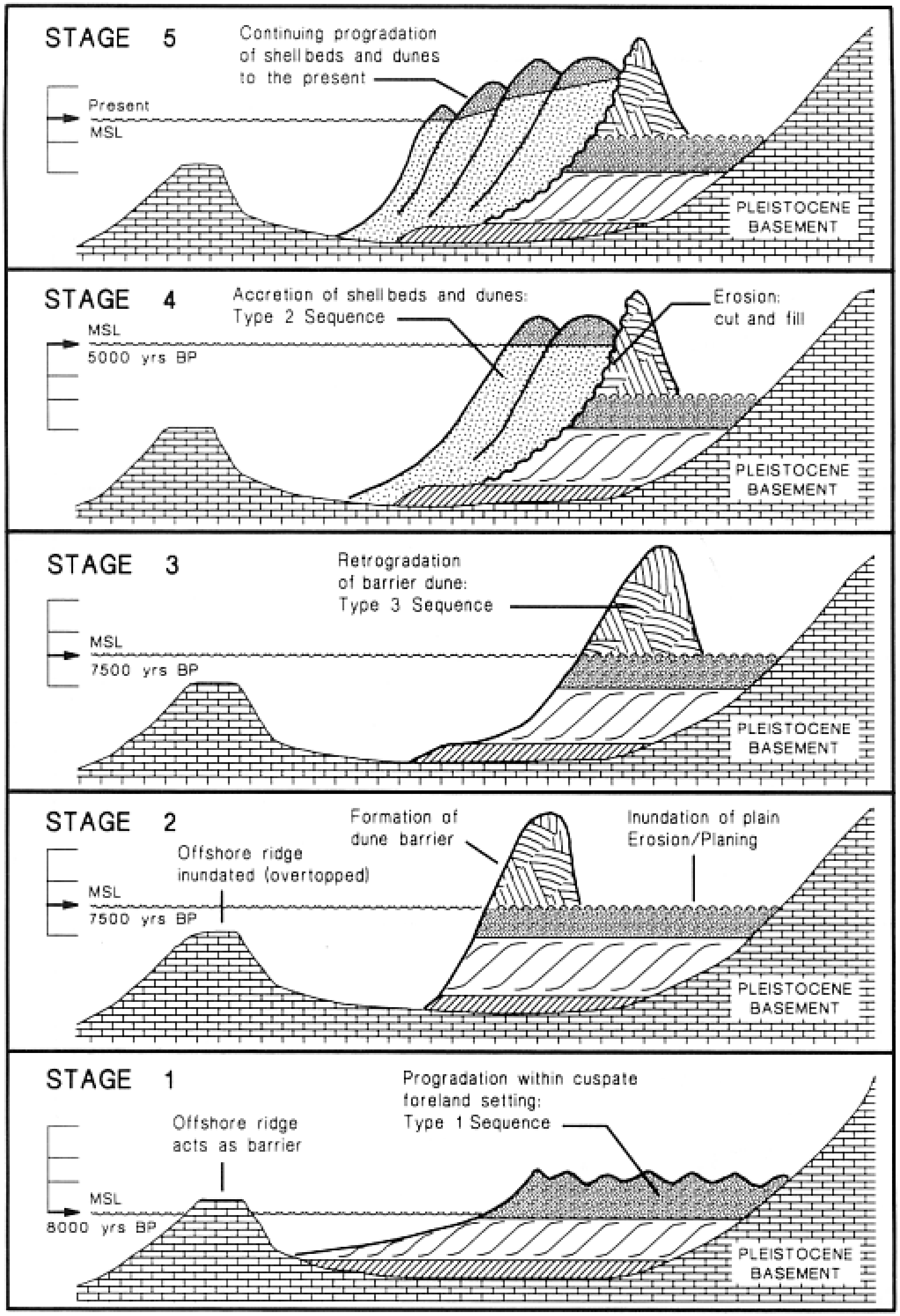

Figure 28: The evolution of the coast in the Bouvard Reefs area in cross-sectional view (after Semeniuk 1996)

The Study Area provides excellent examples of the linkage between stratigraphy and hydrology useful to developing models of mesoscale and microscale patterns in hydrology and hydrochemistry. These models are especially important in understanding the maintenance of wetlands and ecosystems. Such models, exist elsewhere globally, but the specific Quaternary limestone and quartz sand stratigraphy that underpins the wetlands and peripheral wetland ecosystems of the Yalgorup Plain region is unique to the Study Area.

The stromatolites/thrombolites in the Study Area are a significant feature of the region. In the first instance they are Internationally significant in that as stromatolites/thrombolites they are not common as global features. Though occurring on the north shore of Lake Richmond, and in Lake Thetis, and in local sites in the Eyre Peninsula, they not commonly documented elsewhere around the world. Moreover, most of the stromatolites/ thrombolites in the Eyre Peninsula region are relict, having formed several thousand years ago with higher-than-present water levels when sea level was 2 m higher. Stromatolites, or algal mats, that occur in hypersaline tidal flat environments (*e.g.*, Shark Bay, or western Persian Gulf) are not comparable to inland lake stromatolites/thrombolites, and so those along the shores of inland lakes assume International significance.

The stromatolites/thrombolites of the Lake Clifton system are significant for several reasons: they form a shore-parallel wedge along the limestone eastern shore of the lake; they have been planed, and reflect the variable sea level history and hence water level history in the region; and they are in a specific hydrochemical setting of hyposaline water. Structurally, they exhibit domes, and sheets, and diagenesis of planed structures.

These stromatolites/thrombolites are at the least of National significance, but with the ensemble of features they portray in their lateral extent as a shore-parallel wedge body, in their stratigraphic geometry, their association with limestone-sourced groundwater (as compared to the Lake Thetis and the Lake Richmond systems that reside in Holocene dune sand), in their preservation of a variable water level with accompanying truncation and diagenesis, and their internal history, they are Internationally significant.

9.0 Geoheritage

The significance of the natural features of the Study area in terms of geology and geomorphology fall into the realm of geoheritage and geoconservation. This section on Geoheritage features of the Study Area deals first with some background information and theory of matters dealing with geoheritage and geoconservation in terms of:

1. Concepts of geoheritage and geoconservation
2. What constitutes geoheritage, and a definition of other terms
3. Previous lists of areas/sites selected for geoheritage in the Study Area Background
4. Key geoheritage features of international, national and State-wide significance

9.1 Concepts of geoheritage and geoconservation – a background

Geoheritage and geoconservation are concerned with the preservation of earth science features, such as landforms, natural and artificial exposures of rocks, and sites where geological features can be examined. In this report, geoheritage is synonymous to the idea of "earth heritage" of Doyle *et al.* (1994). Geoheritage focuses on the diversity of minerals, rocks and fossils, and petrogenetic features that indicate the origin and/or alteration of minerals, rocks and fossils. It also includes landforms and other geomorphological features that illustrate the effects of present and past effects of climate and Earth forces (McBriar 1995). Geoconservation derives from geoheritage, in that it deals with the conservation of earth science features. Globally, it has become important because it has been recognised that Earth systems have a story to tell, and that they are linked to the ongoing history of human development, providing the resources for development, and a sense of place, with historical, cultural, aesthetic, and religious values. In addition, Earth systems are the foundation of all ecological processes and part of the heritage of the sciences (Torfason 2001).

The international literature shows that geoheritage, focused on geology and geomorphology, globally, is now important for local cultural reasons, natural resource management, land management, research, education, and tourism. As a result, there are various international and intra-national bodies set up for geoconservation, with agreements, conventions, and inter-governmental initiatives. A major outcome of this international collaboration is that there are now various global to local inventory-based classification system for identifying and listing sites of geoheritage significance. The international literature characterises geoheritage as primarily relating to sites of mineral or fossil locations, type sections, classic locations that illustrate Earth history, and locations where Earth processes are operating today, and locally with particular emphasis on classic sites where some principles of geology were first crystallised. While pursuit of geoconservation has resulted in the preservation of sites of geoheritage significance for science and education, and an apparent exclusion of such sites from further developments, an additional, unexpected outcome from geoconservation has been social and economic benefits, *e.g.*, geotourism and geoparks.

To date emphasis on geoconservation and geoheritage has been focused in the United Kingdom and Europe, as they are the birth place of geology and geoconservation. As such they have many globally unique locations and sites that classically portray the history of the Earth, locations where concepts of Earth processes and products were first described, and sites that are part of our Western Philosophy and Scientific History (and as such, essentially are outdoor Museums of cultural and scientific history). However, Western Australia itself has its own geological story to tell (Brocx & Semeniuk 2007). It offers remarkable, unique, and different geological and geomorphological features of global importance - the Shark Bay stromatolites, the Jack Hills zircon crystals, the mound springs of the Great Sandy Desert, amongst many others. For this reason, Western Australia can offer sites of special significance to the global network of geoconservation.

The Yalgorup Plain area and surrounding region geologically is significant for a range of natural history features, ranging from Earth Science features to ecosystem features to biodiversity aspects.

In the realm of Earth Science, which is the focus of this report, this region contains many geological features at various scales that are of International to National to State-wide geoheritage significance. This document of course concentrates on the natural history geological and geomorphic features of heritage value in the Yalgorup Plain area and surrounding region to identify those sites that are of geoheritage significance.

9.2 What constitutes geoheritage, and a definition of other terms

Geoheritage and geoconservation are concerned with geology, so it is worthwhile to explore what constitutes the science of geology and hence, what may be encompassed by the umbrella of geoheritage and geoconservation. Geology needs to be defined in this report, because it will be argued that whatever is encompassed under the umbrella of geology will be encompassed by the notions of geoheritage and geoconservation. After all, geoconservation is merely the conservation of "all things geological". To many readers, the idea of what constitutes geology may be axiomatic, however, this report will delve into areas that traditionally may not be viewed as part of geology by environmental scientists and land managers, hence a discussion of its scope is necessary.

The term geology, often used synonymously with Earth Sciences, is a diverse discipline. Geology and its subdisciplines may overlap with other disciplines such as Chemistry (*e.g.*, crystal chemistry and geochemistry are subdisciplines both of Geology and of Chemistry, and the study of crystal deformation and crystal lattice defects is carried out in Geology, Material Sciences, and in Engineering). All the subdisciplines of Geology should be considered to be a part of Geology *sensu stricto* where particular subdisciplines are oriented in their endeavour to the study of the Earth, even if the same subdiscipline is shared by another science. This is important, because this report contends that the full scope of what constitutes Geology should be within the scope of what could be considered to be of heritage value, and what is considered to be of geoconservation value.

The scientific discipline of Geology involves subsidiary disciplines of igneous geology, metamorphic geology and sedimentary geology, igneous, metamorphic and sedimentary petrology, structural geology, mineralogy, palaeontology, geomorphology, pedology, hydrology and surface processes such sedimentology (see Glossary of Geology; [Bates & Jackson 1987]). This traverses a wide range of scales: at mega-regional scale it includes global tectonics, mountain building, and landscape evolution; at smaller scales, it includes Earth surface processes such as weathering, erosion and sedimentation, involving ice, water, and wind; and at microscale, it includes diagenesis, crystal defects and deformation, amongst others. Chemically they involve studies of precipitation, cementation, solution, and alteration at all scales (Wilson 1954).

In this report, the term geoheritage is used, following Brocx & Semeniuk (2007) in the following manner:

Globally, nationally, state-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference.

While geoheritage concerns the heritage of features of a geological nature, geoconservation is the action that works towards the preservation of such sites if they are significant. Etymologically, it combines the action of conservation with "geos" (the Earth), implying conservation specifically of features that are geological. Geoconservation involves the evaluation of geoheritage for the purpose of conservation and land management, leading to the protection of important sites by law. The scope of Geoheritage is illustrated in Figure 29.

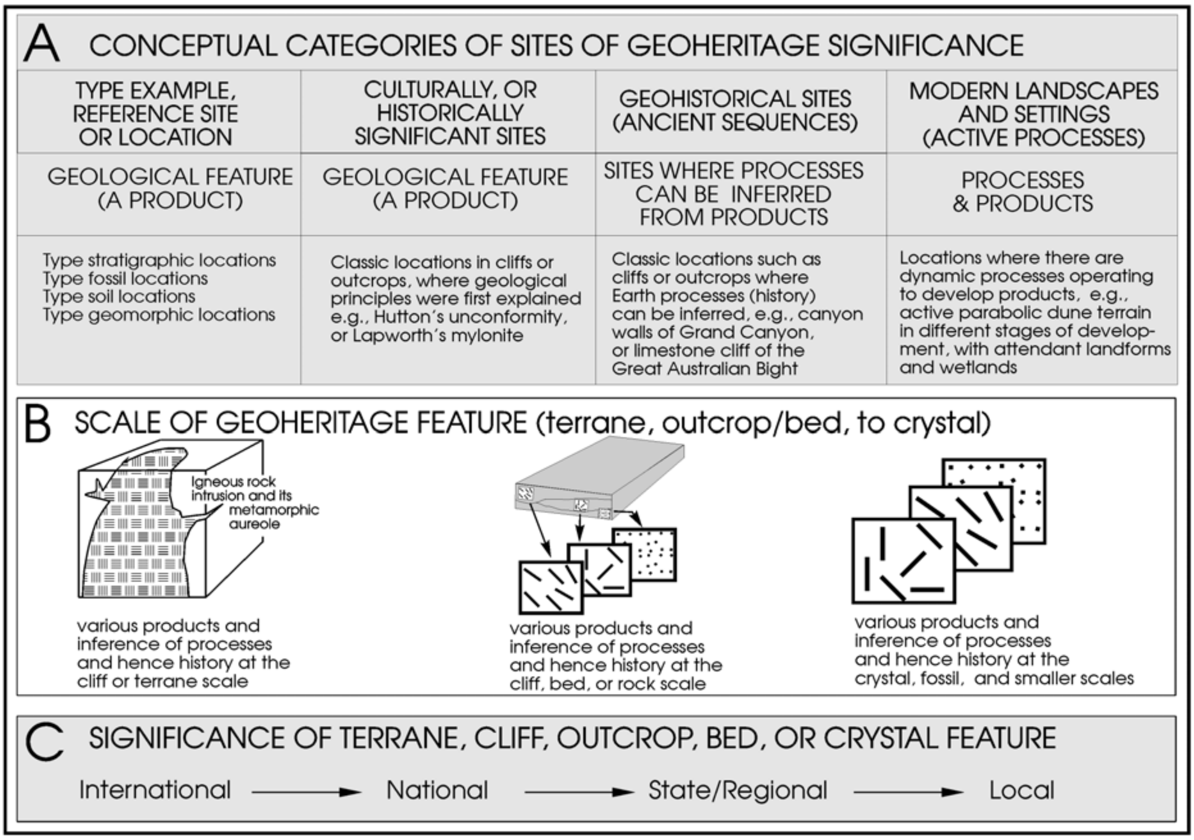

Figure 29: The scope of what constitutes geoheritage.

Scale is important to consider in geoheritage and geoconservation, because sites of significance can range in size from that of landscapes and geological phenomena at montane-scale, to that at the scale of a crystal (Brocx & Semeniuk 2007). A review of the literature shows that in many locations of the world, geological sites are important because of crystal-sized phenomena, and crystal fabrics, because it is often at this scale that the story of the Earth unfolds (the snowball garnets of Vatterbotten, Sweden, Barker 1998; or the zoned zircons from Jack Hills in Western Australia, Wilde *et al.* 2001). At the next scale, important geological phenomena of geoheritage significance are represented by dinosaur footprints, fossil sites such as the Precambrian Ediacara fauna in South Australia (Glaessner 1966), the Cambrian Burgess Shale fauna in Canada (Gould 1989), or Hutton's classic unconformity site (Hutton 1795, cited in Dean 1992). Important geological and geomorphological phenomena continue to occur in increasing scale, right up to the scale of mountain ranges and major drainage basins.

In Australia, a large range of geological and geomorphological features of geoheritage significance, and criteria for their selection are described and discussed by Joyce (1995), Grimes (1995), and Kiernan (1997), amongst others. In the context of scale discussed above, these authors illustrate a wide variety of geological and geomorphological features of geoheritage significance, and from their examples it is clear that there are sites of geoheritage significance that occur at various scales. This is summarised in Figure 30 and Table 2.

Table 2: Examples of geological phenomena at different scales (Brocx & Semeniuk 2007)

Mountain range scale or drainage basin scale
The Grand Canyon (Holmes 1966), geomorphologically illustrating an entrenched river meander cutting down to a new base-level, pacing uplift of a plateau, and geologically illustrating unconformities, and a sequence from Precambrian into the Palaeozoic
Archaean craton structure, folded greenstones, and Proterozoic dykes in the Pilbara Craton (Hickman 1980; Griffin 1990), geologically illustrating a complex array of rounded intrusive granitoids rimmed by greenstones, and cross-cut by a variety of younger dykes
Linear dune fields from the Great sandy Desert (Veevers & Wells 1961), geomorphologically illustrating a complex variety of dune forms in this desert from straight linear, to branched, to tuning fork
Large outcrop scale
Hutton's unconformity, at Jedburgh (Hutton 1795, cited in Dean 1992), a classic location showing the cycle of deposition, induration, upheaval, planation, and further deposition in the Earth's crust
Lapworth's mylonite, along the Moine Thrust (Lapworth 1885), a classic location first used to illustrate the milling of rocks along a major fault
Interlayered black basalt dykes and granitic gneiss, East Greenland (in Myers 1997), the result of the initial rifting between North America and Europe
Bedding scale
Dinosaur footprints in the Broome Sandstone at Gantheaume Point near Broome (Geological Survey of Western Australia 1975), illustrating dinosaurs ambulating across tidal flats in the Mesozoic
Precambrian Ediacara fauna from South Australia (Glaessner 1966), illustrating the oldest invertebrate fauna in the world
Cambrian fauna from the Burgess Shale in Canada (Gould 1989), illustrating a unique, complex and diverse fauna in Cambrian times
Crystal scale
snowball garnets of Vatterbotten, Sweden (Barker 1998), illustrating rotation under shear of crystals and their spiralling incorporation of surrounding layered matrix
orbicular structures of the Thorr Granodiorite of Donegal, Ireland (Pitcher 1993) illustrating concentric whisker crystal formation under delicate conditions of growth, diffusion and cooling
zircons from Jack Hills in Western Australia (Wilde *et al.* 2001), so far, the oldest crystals in the world, showing the Earth was already solid 50 million years after its formation

Significance in geoheritage and geoconservation is assigning of a value to a natural geological or geomorphological feature. While significance is noted in many works dealing with geoconservation, the various levels of significance, *i.e.*, international, national, State-wide, regional, to local, has not been adequately addressed or defined. Levels of significance is a matter that needs to be addressed in classification and site selection, and be incorporated into any planning and management strategy so that geoconservation can be addressed in local and regional issues, as well as the protection of sites of international and national importance. The level of importance attributed to a given feature of geoheritage significance is related to one of two factors:

1. how frequent, or common, is the feature within a scale of reference; and
2. how important is the feature intrinsically or culturally (see Figure 31, after Brocx & Semeniuk)

In the first instance, if a geological feature is common at the local scale, and common everywhere throughout the region, and everywhere throughout the nation, and occurs generally throughout the globe, then it is not significant locally, Regionally, Nationally or Internationally. Calcite crystals cementing dune sand are an example, and their occurrence locally, Regionally, Nationally or Internationally is not significant. Similarly, but on a larger scale, aeolian cross lamination in Pleistocene calcarenite, such as in the coastal zone of the Swan Coastal Plain (Fairbridge 1950; Semeniuk & Johnson 1985; Playford 1988) is another example: this feature is common throughout many areas (McKee & Ward 1983), locally, Regionally, Nationally or Internationally, and hence is not significant. If, on the other hand, a geological feature occurs once or infrequently at the local scale, but occurs at that same frequency through the region, and nationally, and globally, then it is feature significant at the local scale.

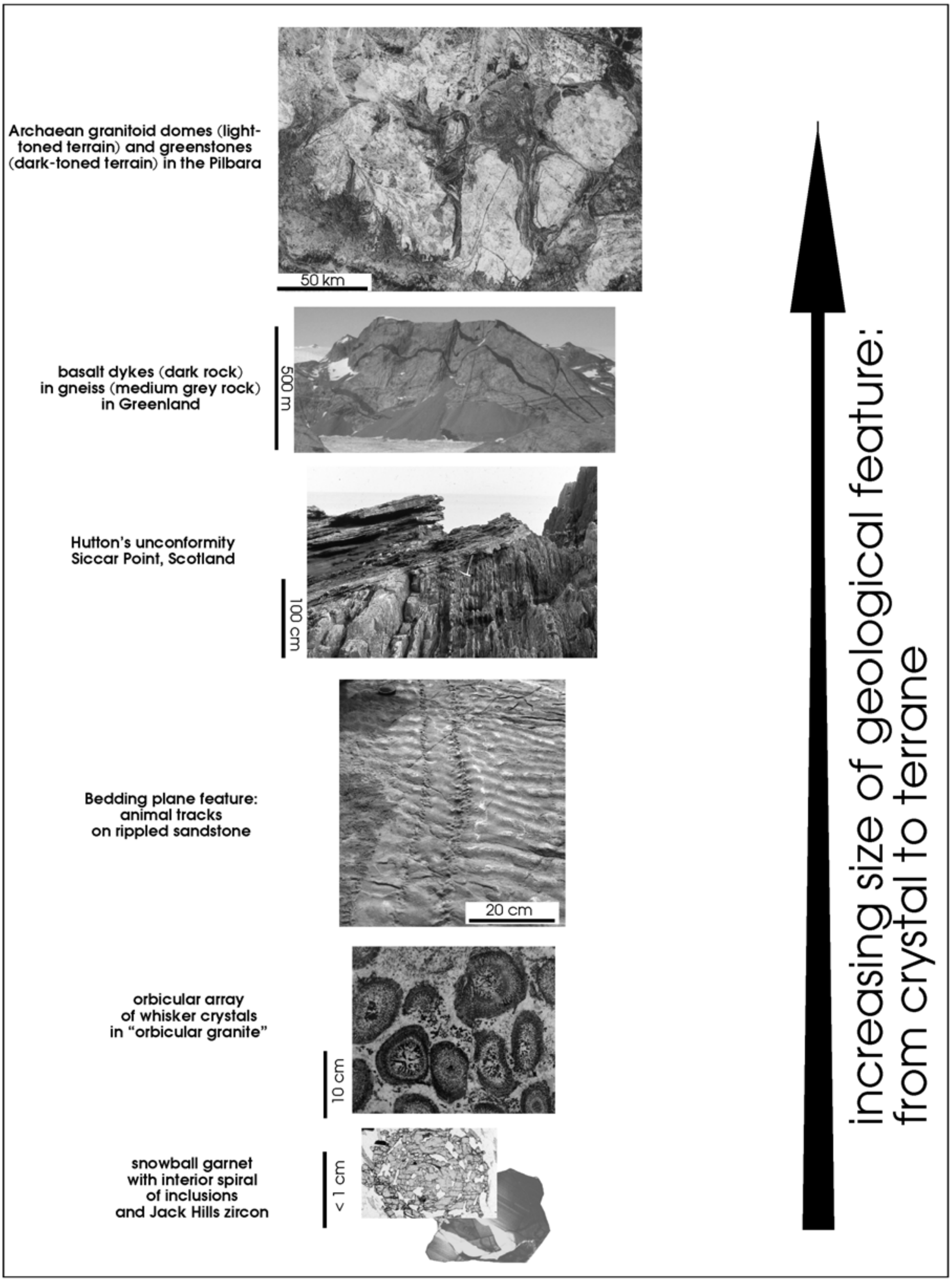

Figure 30: The scale of features encompassed by geoheritage.

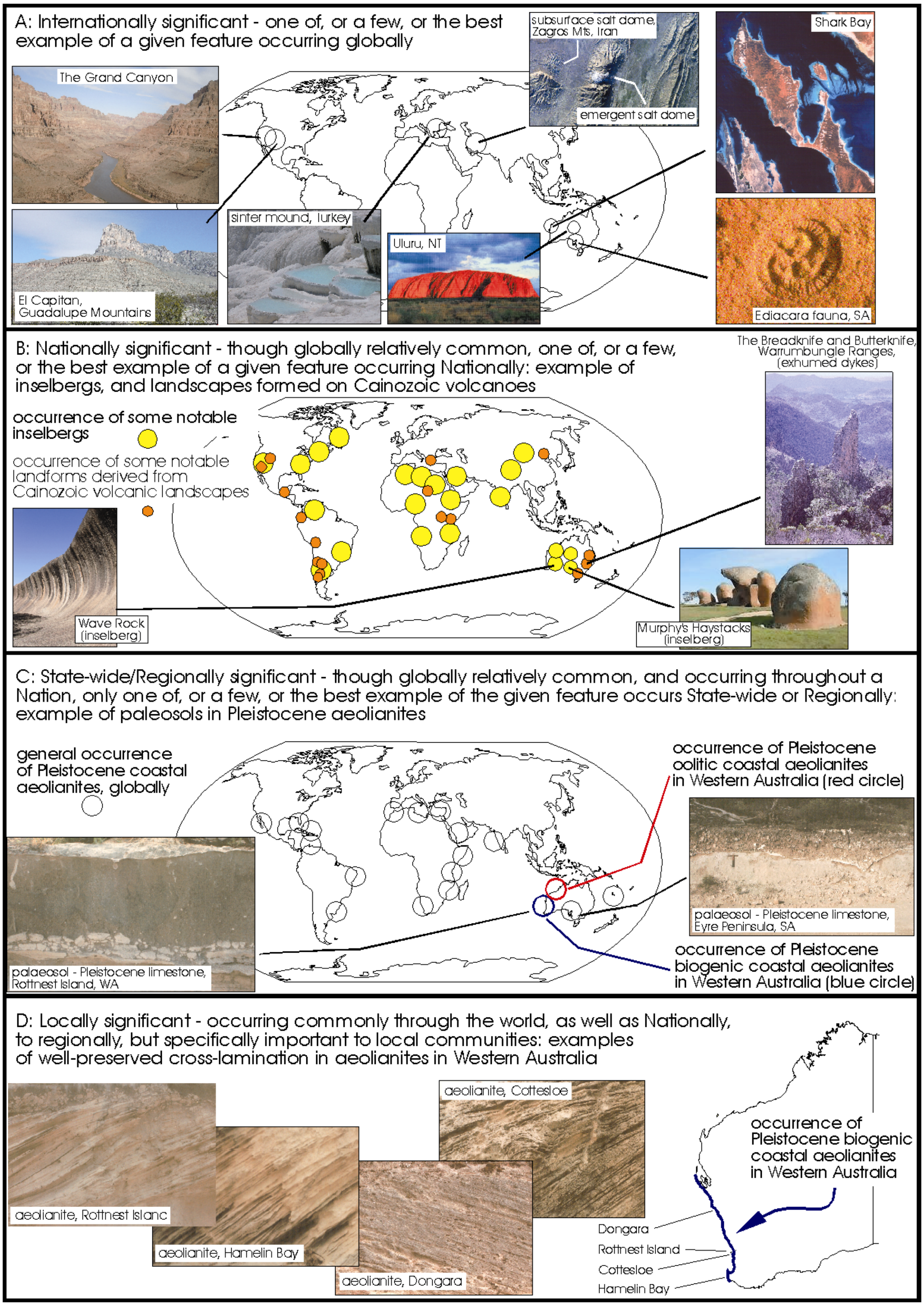

Figure 31: Criteria for assessing the significance geoheritage features.

However, if a geological feature occurs once or a few times within a nation (*e.g.*, inland stromatolites occurring at Lake Clifton, Lake Richmond, Lake Thetis, and some lakes in the Eyre Peninsula in South Australia), then it is of national to international significance. And if a geological feature occurs only once, or a few times world-wide (the tidal flat stromatolites of Shark bay, and the zircon crystals of Jack Hills), then it is a feature of International significance.

The Australian Heritage Commission (1990), similarly, set out criteria to assess sites that are significant enough to be placed on the Register of the National Estate, but there are several deficiencies: for instance, there is no explanation of what is considered to be significant (*i.e.*, the criteria are broadly worded, and there is no yardstick or comparative measure with wording such as "the geological site must be a unique feature in Australia to be considered as highly significant" to enable readers to positively identify sites of significance); there are no comparative examples of significance, nor grading of significance from "highly significant" to moderately significant" to "of low significance", and no reference base to review and compare the attributes of sites already in the conservation estate with sites to be added or in some cases replaced with better examples. Later, the Australian Heritage Commission (Cairnes 1998) dealt with significance, identifying it as the process of assessing the importance of a site. The Australian Heritage Commission (1990) identified *types* of heritage significance (*viz.*, natural, indigenous, and historic cultural), providing criteria of significance (*e.g.*, cultural phases and the evolution of ecosystems; rarity; research, teaching; representativeness; amongst others, as found in the *Australian Heritage Commission Act 1975*) which can be individually graded 1-10, and outlining how "statements of significance" could be prepared.

Semeniuk (1986b), Semeniuk & Semeniuk (1987, 2001) and Brocx & Semeniuk (2007) directly addressed the issue of significance in their work on mangrove coasts, inland wetlands, and sites of geoheritage importance on the Swan Coastal Plain, and geoconservation for Western Australia, respectively, by developing a practical tool in providing scales of significance and criteria for their recognition. Their work, in principle, is applicable to assessing sites of geoheritage significance in general, and in providing grades of "significance". Significance is ranked according to levels or degrees, as follows:

International
National
State-wide
Regional
Local.

These levels of significance listed above have been used Internationally, Nationally in Australia, and within Western Australia, and a definition of these terms, based on Brocx & Semeniuk (2007), with examples of natural features Internationally, Nationally and within Western Australia are presented in Table 3. The examples used in Table 3 provide a comparative background on levels of significance

Table 3: Definitions and examples of levels of significance for sites of geoheritage significance; examples ranging from the very large scale (*e.g.* The Everglades) to crystals (Jack Hills zircons) are as a comparative background on levels of significance

Significance	Definition	Examples	Rationale
International	only one, or a few, or the best example of a given feature occurring globally, hence it is globally unique, rare, or uncommon; or performs a function in a global network	1. Everglades, Florida, USA; 2. carbonate deposits, Roebuck Bay, WA 3. sinter and springs, Pamukkale, Turkey 4. tidal flat columnar stromatolites, Shark Bay; WA 5. Jack Hills zircons, WA	Globally unique systems or geological features
National	while it may be present elsewhere globally, only one, or a few, or the best example of a given feature occurring nationally; hence it is Nationally unique, rare, or uncommon; or performs a function in a National network	1. Permian/Precambrian unconformity, Halletts Cove, SA 2. volcanic landforms, Warrumbungle Ranges, NSW 3. Murphy's Haystacks, Eyre Peninsula, SA 4. Wave Rock, near Hyden, WA 5. the Pinnacles at Cervantes, WA	unique systems or geological features within a given Nation, or performs a function in a National network
State-wide	while it may be present elsewhere globally or nationally, only one, or a few, or the best example of a given feature occurring State-wide; hence in the State it is rare, or uncommon; or performs a function in a sub-national network	1. karst features in southern Western Australia 2. Leschenault Peninsula barrier dunes, WA 3. the buttes in the NW Pilbara region, WA 4. Pleistocene rocky shore stratigraphy exposed in limestone cliffs along the Perth coast, WA 5. orbicular granite, Mount Magnet, WA	unique systems or geological features within the State
Regional	while occurring elsewhere globally, nationally, or State-wide, only one, or a few, or the best example of a given feature occurring in the Region; hence it is uncommon or rare in the Region; or performs a function in a regional network	1. Lake Gnangara on the Swan Coastal Plain, WA 2. conglomerate outcrop at Nannup, WA 3. Bunbury Basalt outcrop at Bunbury, WA 4. mesa formations, southwestern Pilbara region, WA 5. specular haematite crystals, Koolyanobbing, WA	important systems or geological features in the Region, and for the coastal limestone, exposure of atypical stratigraphy
Local	the natural history feature is important only to the local community	limestone cliffs along the Perth coast, illustrating well-formed cross-lamination in the limestone	important to the local community and schools

9.3 Previous lists of areas/sites selected for geoheritage in the Study Area

Various databases were accessed to determine what already has been assessed as of geoheritage significance in the Study Area; there are:

1. Carter (1987) who completed a study in Western Australia of important geological localities outside the Perth region, describing their significance and value protection and presentation.; those from the Study Area are listed in Table 5 below;
2. The Australian Heritage Commission (AHC), which accepted nominations on sites of National Significance, listing them on the Register of National Estate.
3. The listings in the EPBC Act
4. The Geological Survey of Western Australia, which recently commenced a database (inventory) of sites of geological significance (geosites), based on their selection of sites from Carter (1987); those listed so far are presented in Table 6;
5. in-house V & C Semeniuk Research Group R&D information as part of its R&D endeavour, has been investigating sites of geoheritage significance in the Study Area since 1976 (some of the work has been published in Semeniuk & Semeniuk (2001), and Brocx & Semeniuk (2007), but the bulk of the information remains in-house and as yet unpublished; what is relevant to the Study Area Hill has been described in this report.

The features of the Yalgorup Plain were not listed for geological sites or for geosites by Carter (1987), AHC, or the Geological Survey of Western Australia.

The area of the Yalgorup National Park, however, has been listed by the EPBC Act.

The Yalgorup Plain area was identified by Semeniuk & C A Semeniuk (2001) as being of geoheritage significance (Figure 32).

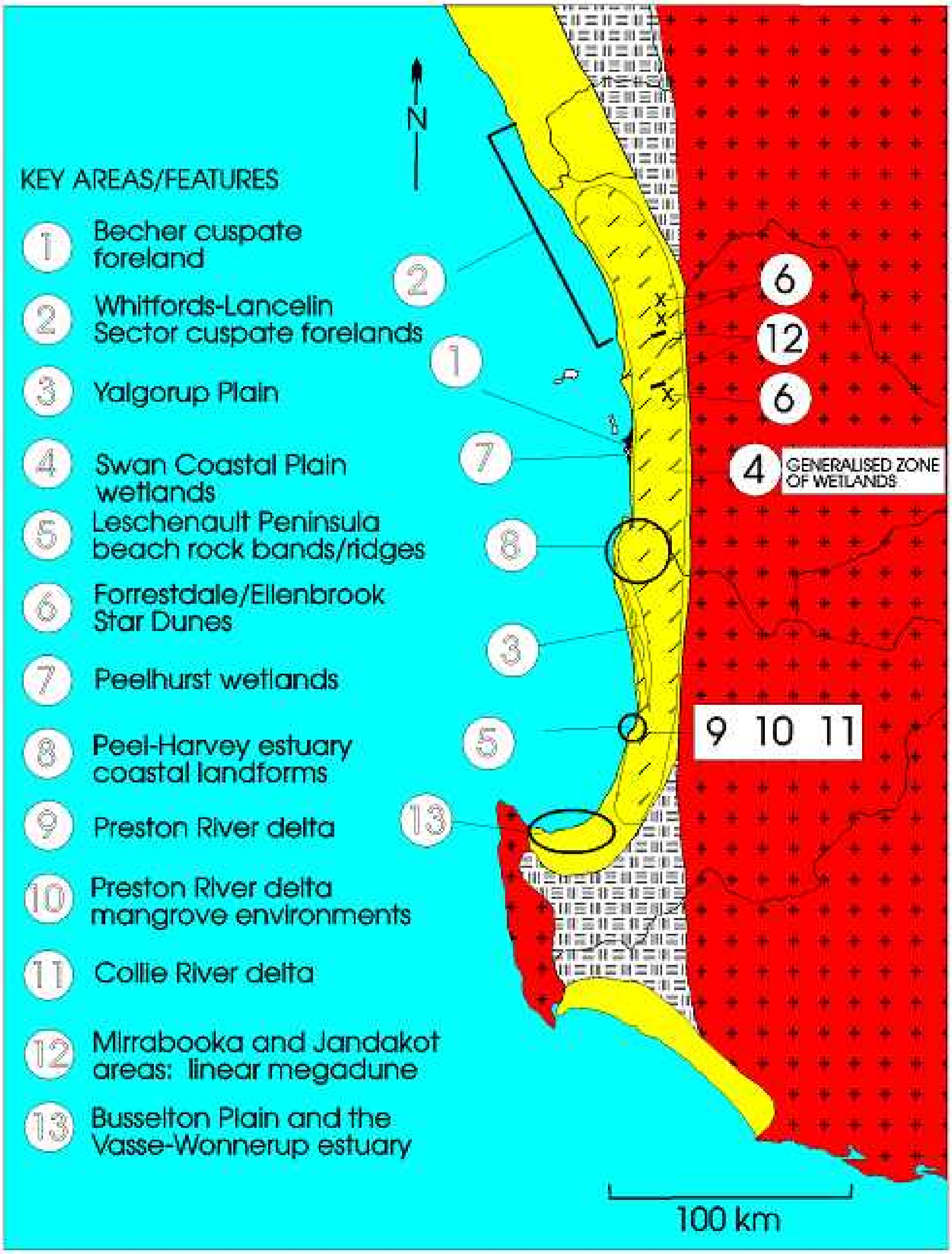

Figure 32: The Yalgorup Plain area identified by Semeniuk & C A Semeniuk (2001) as being of geoheritage significance as location 3.

9.4 Key geoheritage features of International, National and State-wide significance

The key geoheritage features of International, National and State-wide significance are assessed in Table 4 below according to the criteria developed by Brocx & Semeniuk (2007). The detailed information leading to this assessment has been presented throughout this report. The features to be assessed are:

1. Pleistocene stratigraphy, landforms and history
2. south to north style of the Holocene barrier dune
3. Holocene barrier history
4. wetlands
5. record of a rising sea in a bathymetrically complex coast
6. stratigraphy linked to hydrology
7. stromatolites/thrombolites

Table 4: Assessment of key geoheritage features in the Study Area

Geoheritage feature	**Level of significance**
Pleistocene stratigraphy, landforms and history	International
south to north style of the Holocene barrier dune	National
Holocene barrier history	International
wetlands	National (potentially International)
record of a rising sea in a bathymetrically complex coast	International
stratigraphy linked to hydrology	National
stromatolites/thrombolites	International

10.0 Discussion and conclusions

Under Geological World Heritage Criteria, the Yalgorup Plain is a page in the geoarchive of the history of the Earth. It demonstrates globally unique products of active and past process that include coastal and marine processes.

The geoheritage features and their level of significance assessed in this report suggest that the Pleistocene stratigraphy, landforms and history are Internationally significant, the south to north style of the Holocene barrier dune is of National significance, the Holocene barrier history is Internationally significant, the wetlands in the Study Area are Nationally significant (and potentially Internationally significant), *i.e.*, the line of lakes and limestone ridges appear to be globally unique, the record of a rising sea level in a bathymetrically complex coast contained in the landforms and serigraphy of the northern part of the study Area are Internationally significant (*i.e.*, the complex nature of the most seaward barrier which is globally unique), the stratigraphy linked to hydrology is Nationally significant (for instance, the formations are hydrologically and hydrochemically acting as separate bodies and are interrelated, and limestone ridges and lakes are complex hydrologically), and the stromatolites/thrombolites while Nationally significant and listed in the EPBC Act, are also Internationally significant.

The peripheral wetlands of the Leschenault Peninsula system serves as a model for the lake Preston area, and shows that peripheral wetlands along the shores of Lake Preston which is a Ramsar site will be influenced by alteration to such seepage. The Preston Barrier is stratigraphically more complex than Leschenault Peninsula, and hence more hydrologically complex and this has implications for the hydrology and freshwater seepages for the peripheral wetlands of the Preston Barrier
A summary of the geology and geomorphology of the Study Area across the Yalgorup Plain is shown in Figure 33.

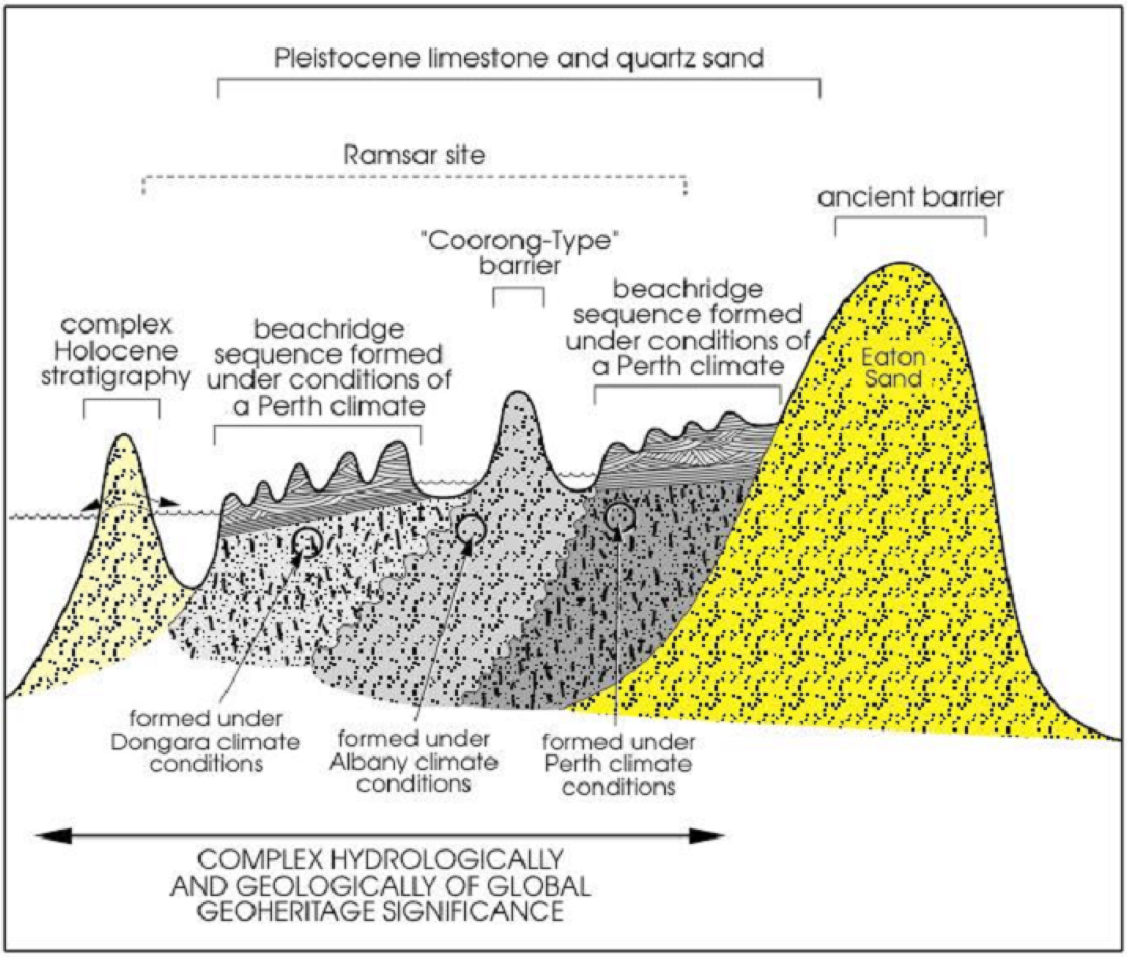

Figure 33: Summary of key geomorphologic and geologic features in the Study Area

10.1 Predicted impacts of developments and constraints

The geoheritage significance of the Yalgorup Plain and the Preston Barrier leads on to a discission of the predicted impacts of any developments in this area and types of constraints that exist in the area.

Clearly, the case has been made in this report that this area of the Yalgorup Plain is an Internationally significant classroom, not only for one geological feature, but for a range of features, and for a ranges of geological features that are interrelated. Urbanisation and other types of development will impact on the natural values of this region.

For instance, any urbanisation or other types of development on the Pleistocene stratigraphy, landforms and history will adversely impact on the natural values of a feature that has International significance. Land clearing associated with urbanisation or other types of development clearly will compromise the nature landscape features of the Pleistocene landforms, and groundwater alteration will affect the diagenetic “wilderness” of the limestone system.

Similarly, because there is a south to north variation in the Holocene barrier dune that is in parcels, land clearing associated with urbanisation or other types of development will affect the interrelated integrity of the barrier. The Holocene barrier history, as preserved in the stratigraphic record, is a subsurface feature, and if the terrain is not markedly modified by landscaping this international feature would still be present. However, the effect of this stratigraphy on groundwater and vegetation is unknown, and needs to be rigorously investigated to determine whether merely leaving the stratigraphy intact but clearing the land will affect and destroy vegetation that is linked geochemically and hydrologically to the complex subsurface stratigraphy. The same argument applies to the stratigraphy and landforms record a sea rising into a bathymetrically complex coast during the early Holocene, and the response of this complex coast to a variable sea level record. This geological, stratigraphic and geomorphic ensemble is an outstanding feature of global importance, and should not be compromised by any development.

The wetlands in the region, while they would not be directly built upon or developed, are targets of altered hydrology and hydrochemistry. Any urbanisation or other types of development where they alter groundwater patterns or carry risk of contributing contaminants such as nutrients, need to be constrained or avoided. The impacts would be on the water quality of the wetlands, the water regime of the wetlands, and the peripheral vegetation of the wetlands.

This aspect is diagramatically summarised in Figure 34. There are 4 aspects to Figure 34.:
1. urbanisation on a dune system will carry with it contamination of the groundwater with nutrients and other contaminants;
2. there will be export of nutrients and other contaminants towards the Lake and specifically to the peripheral vegetation;
3. the peripheral vegetation will be altered in floristics and structure; and
4. these effects will be within a Ramsar site, that is obligated to be protected by International Treaty

This rationale of avoiding the alteration of hydrology and hydrochemistry applies also the areas where there is clear linkage of stratigraphy to hydrology, as this feature is a aspect of geoheritage significance..

Finally, as with the wetlands, the stromatolites/thrombolites are sensitive ecological/geological features, and alteration of groundwater regimes in terms of flow rates and rising and falling of the hinterland groundwater table, and any alteration of hydrochemistry (such as contribution of contaminants such as nutrients) runs risk of affecting and damaging these internationally significant features.

Figure 34: Summary of main impact of development on the barrier dunes

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