

Dune slacks in Western Australia

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Abstract

This paper provides a review and revision of the term 'dune slacks' that was originally developed as a concept in the United Kingdom and Northern Europe. Using global and Australian case studies, we examine the types of dune slacks, their attributes, the range of their formational processes, and their evolution in relation to coastal setting, geomorphic processes and hydrology. Based on the processes and pathways of coastal dune development and evolution along the Western Australian coast and global variations, the original concept of dune slacks is expanded, particularly in the area of hydrological setting. Western Australia presents a wide range of coastal types, from rocky shores to depositional sandy coastal to tidal systems to erosional sandy coasts, to dune-dominated coasts, but dune slacks are found in only six sites, located mainly in the southwestern and southern regions of the State. They are developed at Whitfords, the Rockingham, Becher Point and Secret Harbour area, the Meerup/Yeagarup area, Reef Beach near Albany, the Warramurrup Dunes near Bremer Bay, and the Bilbunya Dunes in the Israelite Bay area. However, at some sites there are a range of coastal dunes settings wherein are developed different types of dune slacks. The Rockingham, Becher Point and Secret Harbour area, for instance, has depositional coastal settings to develop a dune slacks, and erosional coastal setting to develop β dune slacks. In this paper, the dune slacks of Western Australia are described in terms of regional setting, dune sand type and its CaCO_3 content, and dune slack water salinity and pH. Finally, the regional factors in Western Australia important for development of dune slacks, the occurrence of former dune slacks, and where dune slacks are not developed and why are described and discussed.

Keywords: dune slacks, coastal dunes, Western Australia, hydrology, coastal geomorphology, wetlands

Introduction

While a non-genetic approach to classifying wetlands at a site specific level, based on landform setting and hydrology, was emphasised by C A Semeniuk (1987) and Semeniuk & Semeniuk (1995), there is a place for a genetic classing of wetlands where there is a similar underlying pattern to their formation, *e.g.*, wetlands associated with dune formation, or with karst, or with development of fluvial landforms. A genetic approach to classification forms the basis to identifying wetlands of similar consanguinity, and hence to the identification of wetland suites (C A Semeniuk 1988). The category of wetlands, known as "dune slacks", has affinities with this latter type of classification, regardless of how they may be classified at the site-specific level, (*e.g.*, as seasonally waterlogged or seasonally inundated basins). This is not to imply that all dune slacks belong to the same consanguineous suite, or even that dune slacks along coastal Western Australia belong to the same consanguineous suite, but they do, in their own right, belong to a set or class of wetlands with important attributes in common, such as origin, setting, basin morphology and hydrological regime.

Generally, dune slacks are undescribed wetland systems along coastal Western Australia, though

wetlands that can be classed as dune slacks have been noted, classified as site-specific types, or described by C A Semeniuk (1988, 2007) and Semeniuk *et al.* (1989). Dune slacks occur in Western Australia in Holocene coastal dune settings, extending from Whitfords in the central part of the Swan Coastal Plain on the western coast to Bilbunya on the southern coast, spanning a range of climate types and facing a range of oceanographic settings. This paper reports on their occurrence, variability, and formation in Western Australia, and adds to the global understanding of the variety of dune slack types and their climatic settings.

Western Australia provides opportunity for exploring the limits and definition of dune slacks. Unlike the geographically and climatically limited areas in northern Europe and the United Kingdom, where much of the early work on dune slacks was undertaken, or the local areas in South Africa, Uruguay, and Spain, which provided departures from the earlier concepts, Western Australia provides what is effectively a continuum of environments of coastal dunes with variation across this subcontinent. This variation is expressed in geomorphic setting, coastal dune and coastal landform development, and oceanographic, wind and other climate parameters, which progressively or discontinuously, alter the dune slack forming environments and the style of evolution the dune slack will undergo (or has undergone). In essence, Western Australia provides a classroom where the definition and limits of dune slacks can be investigated.

The first objective of this paper is to trace the origins, and provide a brief history of usage of the term "dune slack," to explore what constitutes wetlands in this category, and what defines the boundaries or range of the class. This paper also examines the present usefulness of the term in the context of the range of wetlands which occur in the coastal dune environment. One impetus for this review has been the growing number of wetland forming processes and settings, identified in coastal areas, which have been amalgamated under this collective term. A rekindled interest in the historic roots and applications of the term "dune slack" has prompted an assessment of its scientific meaning. As a basis to the discussion, reference is made to wetland types in coastal dune settings around the world, with a special emphasis on the coast of Western Australia. Figure 1 illustrates the processes and pathways by which the concepts contained in the United Kingdom and Northern European body of work on dune slacks may be expanded.

The second objective of this paper is to describe examples of dune slacks from Western Australia, which span humid to arid climates, high to low energy shorelines, and erosional and depositional coastal tracts. In a divergence from the traditional way in which dune slacks are characterised, that is a focus on vegetation, in this paper they are described from a geomorphic perspective, which includes and emphasises their setting, origins, underlying parent material, and their combined determinative effects on basic hydrological maintenance, all of which result in a particular wetland type.

This paper is based on extensive fieldwork and mapping. Dune slacks were identified during wetland mapping undertaken between 1980 and 2007 (V & C Semeniuk Research Group 1991, 1994, 1997a, 1997b, 2000, 2006, 2007, 2008). Aerial photography covering coastal Western Australia was used to identify sites for fieldwork, so that every major mobile coastal dune and beach

ridge system was visited by helicopter or by road. In the field, sand was sampled from the dunes surrounding the slacks (as sediment parent to the slacks), and from within the slacks. Pits were used to sample groundwater and stratigraphy. Three of the sites in this paper were intensively studied between 1990–2004 (C A Semeniuk 2007), continuing at one site until 2010. Coring and laboratory description/analyses of sediments/soils follows Semeniuk & Semeniuk (2004, 2006) and C A Semeniuk (2007). Sediment was granulometrically analysed in 1 phi intervals, and calcium carbonate content determined by digestion in 10% HCl. Sediment, soil, and water were analysed at commercial laboratories for Ca, Na, K, Mg, N and P. At each wetland, plant species were identified and cover estimated. The term "dune field" is equivalent to the term "erg".

Origin of the term "dune slack"

In the context of dune slack, the word slack comes from common usage, and derives from the Old Norse word "slakki" which originally meant a hollow on a hillside. In geographic areas where the Norse cultural influence persisted, including elements of the language, "slakki" became the etymological root for words for valleys or depressions in the ground. Over time, the term was applied to such valleys and depressions within the expanses of dunes which occurred in the central and northern coastal areas of the Netherlands, Denmark, Germany, England, Scotland and Wales. Often these valley sites were wet, in contrast to their surrounds.

Among the first uses of the term "slack" and "dune slack" in scientific literature were van Dieren (1934), Tansley (1949), and Ranwell (1959). In these works, "dune slack" had already been modified to mean a damp or wet hollow within a coastal dune terrain, where the water table was seasonally at or near the surface. Thus "dune slacks" became associated with coastal dunes, as distinct from wetlands associated with swales in other dune systems, such as desert linear dunes. They also were strongly linked to two hydrological mechanisms: 1) seasonal inundation or waterlogging, and 2) recharge resulting from the seasonal rise in the regional water table. These features served to separate them from lagoons, "dune lakes" and from remnant fluvial systems (Bayly & Williams 1973; Timms 1982; De Raeve 1987; Leentvaar 1997; Grootjans *et al.* 1998). The hydrochemical system in dune slacks commonly is fresh water, and the underlying parent material is generally nutrient-poor mineral sediment (Willis *et al.* 1959a, 1959b, Jones & Etherington 1971, van Dijk & Grootjans 1993, McLachlan *et al.* 1996; Lammerts & Grootjans 1997; Lammerts *et al.* 2001). Developmental processes in common with all types of dune slack include the input of salt spray, sand mobilisation, and incipient soil development within the basins (Lubke & Avis 1982).

It can be seen from this very brief summary that, with respect to some attributes, the initial general term "dune slack" had been modified in the scientific literature to have some very specific meanings. Firstly, the dune slack was not related to just any dune system, it referred specifically to a hollow in coastal dunes. Secondly, the term hollow was not just any hollow but one subject to seasonal inundation or waterlogging. Thirdly, the water

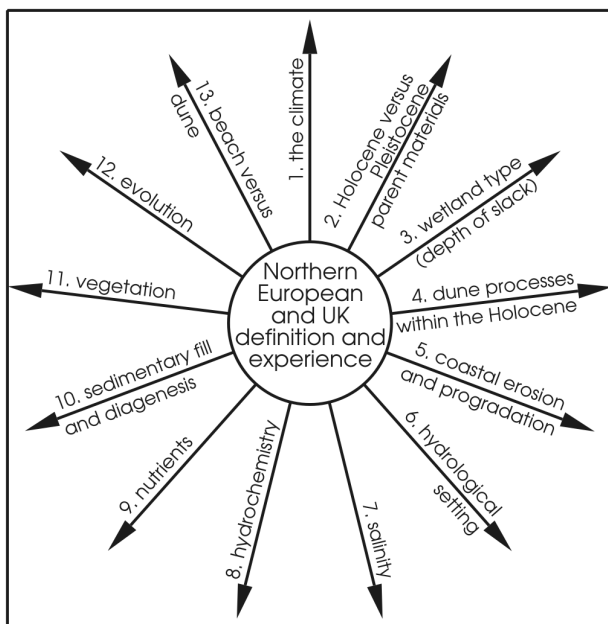


Figure 1. The thirteen possible settings, processes, and pathways by which the original concept of dune slacks, developed in the United Kingdom and Northern European, can be expanded.

in the hollow should be maintained only by groundwater rise, and finally, the chemistry of the dune slack water should be fresh or evolving from brackish (*i.e.*, recently marine-derived) to fresh.

Types of dune slacks

Dune slacks are not as widespread as one would imagine. In coastal locations in similar latitudes, the most common general wetland forms are estuaries and deltas, barred estuaries and lagoons, coastal plains/tidal flats, or seepage lines in cliffed coasts (Bird & Schwartz 1985). Even in beach ridge and dune settings, which are conducive to dune slack formation, there are other types of wetlands, with no relationship to coastal processes and, in dune fields high above the water table, there may be no wetlands in the dune hollows. A further restriction on the definition and concept of dune slacks is the requirements for seasonal fluctuation of the water table and input of fresh groundwater, which suggest a temperate climate setting.

There were attempts by early researchers to identify various types of dune slacks with reference to the origins of their formation (van Dieren 1934), the plant communities within them (Crawford & Wishart 1966; Ranwell 1972), and some aspects of their chemical environments, notably the differences in pH in the groundwater and ion concentrations in the sediments. Van Dieren (1934) identified two types of dune slacks: primary and secondary.

“Primary dune slacks” form on prograding coasts where seaward advancement is rapid and plains of successive beach ridges and swales, beach flats, and spits comprise the coastal landforms. A short term change in offshore energy conditions or supply of sediment may see the recommencement of ridge building along the strandline, thus effectively creating a barrier between the already formed flat or swale and the sea, and cutting off the lowland from marine processes (C A Semeniuk 2007). The initial brackish character of the groundwater in the lowland is slowly replaced by the freshwater influence of a rising water table (Grootjans *et al.* 1998).

“Secondary dune slacks” are formed by wind erosion (van Dieren 1934; Ranwell 1959; Willis *et al.* 1959a, 1959b; Siljeström *et al.* 1994; Grootjans *et al.* 1998; Yan *et al.* 2006). This can take place in an established and vegetated dune massif when a break in the dune plant cover becomes a node for erosion and for re-mobilisation of sand and construction of new dune forms and depressions, or it can occur when the coastal wind forms parabolic dunes and bowls (Short & Hesp 1982; Boorman *et al.* 1997).

Further differentiation of dune slacks using the traditional criteria of pattern of vegetation cover, physiognomy, and composition of wetland plant assemblages was practiced. Pioneer species, plant growth forms and community structure were used to separate younger and older dune slacks (Ranwell 1960; Crawford & Wishart 1966; Ratcliffe 1977; van der Meulen & van der Maarel 1993; Avis & Lubke 1996). Identification of the plant species as indicators allowed Ranwell (1972) to differentiate three categories of dune slack: dry, wet, and semi-aquatic, reflecting the average groundwater level over a period of time. This approach was subsequently

adopted by other researchers (van der Laan 1979; Boorman 1993; Grootjans *et al.* 1995).

Differentiation between acid and base rich dune slacks has been approached in a number of ways. Kaiser (1958), cited in Leentvaar (1997), distinguished between acidic oligotrophic and neutral oligotrophic types, based on pH and calcium content of the water. Emphasis has been placed on acidic and base rich dune slacks in the United Kingdom as part of their conservation programme because of the effects of the groundwater and sediment chemistry on species colonization (Boorman 1993). Lammerts *et al.* (1992) and Grootjans *et al.* (1996) both demonstrated that calcium content in the water is a major determinant of dune slack plant community composition and sediment evolution in a humid climate, and C A Semeniuk (2007) described the gradation and alteration of highly calcareous to more acidic dune slack sediments in a temperate climate.

Already embedded in these early attempts at classifying dune slacks were the seeds of future classification problems. The term “primary dune slack” was applied to both coastal dune and beach settings. Differentiation between acidic and base rich slacks posed questions about slack evolution and the amount of peat fill which could be present in a traditional “dune slack”. Recharge resulting from the seasonal rise in the regional water table, which had formerly been a fundamental attribute of dune slacks, was replaced by a reliance on plant species as indicators of dune slacks and dune slack types. This shift in focus overlooked the fact that the same plant community may colonise seasonal coastal dune wetlands whether they are recharged by groundwater rise, perching of rainwater, seepage, or fluvial input.

The range of formational processes and attributes of dune slacks

In spite of the previous comments upon classification, the scientific literature shows that the term “dune slack” was clearly understood by researchers in the United Kingdom and the Netherlands for a European setting. It immediately identified a group of wetlands with some fundamental similarities which could be used in comparative analyses, and inspired a repository of communal information which has been steadily built upon. It also facilitated international cooperation for the conservation of these wetland types and the rare plant species which characterise many of them. However, increasing research into coastal areas and wetlands outside the United Kingdom and the Netherlands brought to light wetlands in coastal dune settings which exhibited important divergences in geomorphic origin and history, settings, and hydrologic processes. Types of wetlands in coastal dune terrains elsewhere did not always conform to the categories of “primary” or “secondary” dune slacks, and those which did often developed more complex functions as they evolved. It is timely to determine whether the term “dune slack” is still appropriate for this extended range of wetland ecosystems by examining the ways in which these wetlands differ from those first described. The following features have been selected: setting, dune types, water regimes and hydrological mechanisms, and the effect of evolution.

Dune slacks, even initially, could be separated into distinct geomorphic settings:

- a depositional coastal setting associated with the construction of foredunes, beach ridges, beach spits or dune building, and
- an erosional environment of mobile dunes, sand sheets, blowouts and dune residuals.

The depositional setting is usually linked to coastal progradation. Spits and barriers associated with the widening of beaches and development of cusped forelands, tombolos, estuaries and deltas enclose and separate shallow nearshore marine areas to form an ephemeral saline water body. Initially, this body is maintained by marine and tidal processes, but evolves over time, as progradation continues or as the seaward barrier becomes wider and higher, to a freshwater system, maintained by near surface groundwater. In this context, the lagoon or lake is relatively short lived and the phase approaching equilibrium is that of seasonal inundation. On prograding coastlines, a second type of "damp or wet hollow between the dune ridges, where the groundwater reaches or approaches the surface of sand" was identified by Tansley (1949). Examples commonly comprise wide beaches, backed by a foredune and successive dune ridges. The hollows between the low dune ridges and the beach foredune can have various geometric forms: a linear flat floored lowland, a linear to irregular depression filled with conical sand residuals, sand shadow mounds and hollows, or an irregular depression with single or multiple basins. Low lying areas that are close to the water table will form slacks. Depending upon the height of the land surface relative to the water table, inundation or waterlogging will occur. Such wetlands have variously been termed dune slacks (Chapman 1964; Dickinson and Mark 1994; Freitas *et al.* 2007), dune ponds, or dune lakes (Westoff 1954; Bayly & Williams 1973; Timms 1977), or wet swales (Wiedemann 1993; C A Semeniuk 2007). These wet basins are either seasonally inundated or waterlogged, depending on the configuration and position of the water table, relative to sea level and the land surface (C A Semeniuk 2007).

An offshoot of this common type of dune slack formation in a depositional setting, described only recently, is that of the intersection of inter-ridge swales by a rising water table in response to coastal progradation of a cusped foreland and subaerial beach ridge plain (C A Semeniuk 2007). In this example, the constant is the beach ridge plain and the variable is the rising regional water table.

In contrast, dune slacks formed in comparatively stable (non-prograding) coastal settings, where aeolian erosion is the formative process, owe their wet origin to local exposure of the near surface water table and begin as a seasonally inundated basin evolving over time to a drier seasonally waterlogged basin. This exposure of the water table commonly occurs in association with dune migration and deflation of established dune systems (Lundberg 1993). However, there are variable internal factors inherent in this simple system of dune slack formation also. For instance, the surface exposed by wind deflation may not be composed of the same material as the dunes, or the deflation surface may lie at some considerable height above the regional water table, with the "slacks" in both situations relying on hydrological

mechanisms other than inundation or waterlogging by seasonal regional groundwater rise, as described above.

Dune types can also determine the nature of dune slacks (Figure 2). Foredunes and beach ridges have been mentioned in relation to prograding shorelines, and parabolic dunes, chaots and conical hill residuals typify erosional shorelines (Semeniuk *et al.* 1989). However, in many coastal settings, transgressive (ingressing) dunes occur and can extend for considerable distances inland. When transgressive dunes climb established topography or become isolated inland from the main dune field, "intra-dunal slacks" exhibit different characteristics. The basement underlying this type of slack or depression may be bedrock, a calcretised or cemented layer of an older dune, or a buried pedogenic layer, with very different hydrological and hydrochemical properties from slacks underlain by beach or dune sands.

Natural and anthropogenic geomorphic processes can mirror each other in the formation of "dune slacks", but whereas natural processes are part of the present coastal wind and wave regime, and depositional and erosional products, anthropogenic processes, in fact, can occur at times and places which are unrelated and contrary to the geomorphic stage and evolution of the region. Stable vegetated dunes are the template for natural development of parabolic dunes and blowouts. Nodes, where vegetation is undermined and removed occur naturally in coastal systems subject to waves, storms, and persistent winds, initiate development of mobile transgressive dunes. However, dunes can also be destabilised when binding vegetation is removed through anthropogenically-induced effects such as erosion by vehicles, fire, or grazing. Under these latter processes, dune movement can be initialised and slacks may develop in what is no longer a current shoreline dune system, but as a palaeo dune system such as in the older dunes of Donana National Park, or King Island, Tasmania (Jennings 1957; Siljeström *et al.* 1994).

Hydrological mechanisms and water regimes can also vary in different types of slacks. Although dune slacks are generally maintained by a near surface water table, the way in which this occurs can vary. Initially, it was thought that the regional water table was directly intersected and exposed in an inter-dune depression (*e.g.*, the convex profile of the water table described by Willis *et al.* 1959a, 1959b for Braunton Burrows in Devon, and by Ranwell 1959 for Newborough Dunes in Anglesey) or that it rose above the ground surface in response to seasonal rainfall as part of the regional hydrological pattern. However, dune slacks can be maintained through intersection of a local water table. For instance, a localised elevation of the water table can result when a coastal barrier impedes groundwater flow and causes mounding behind a barrier, or when the water table rises in response to overflow seepage from a barred river or barred estuary (Warren River, southern Western Australia). Further, a rise in the water table may result from causes other than rainfall, *e.g.*, the water table rise in response to coastal progradation and a gradually falling sea level (C A Semeniuk 2007).

In addition, there have been descriptions of local low inter-dune areas where rainwater is perched on near surface relatively impermeable peat or clay layers (Bakker 1990, C A Semeniuk 2007). In these examples, the dune

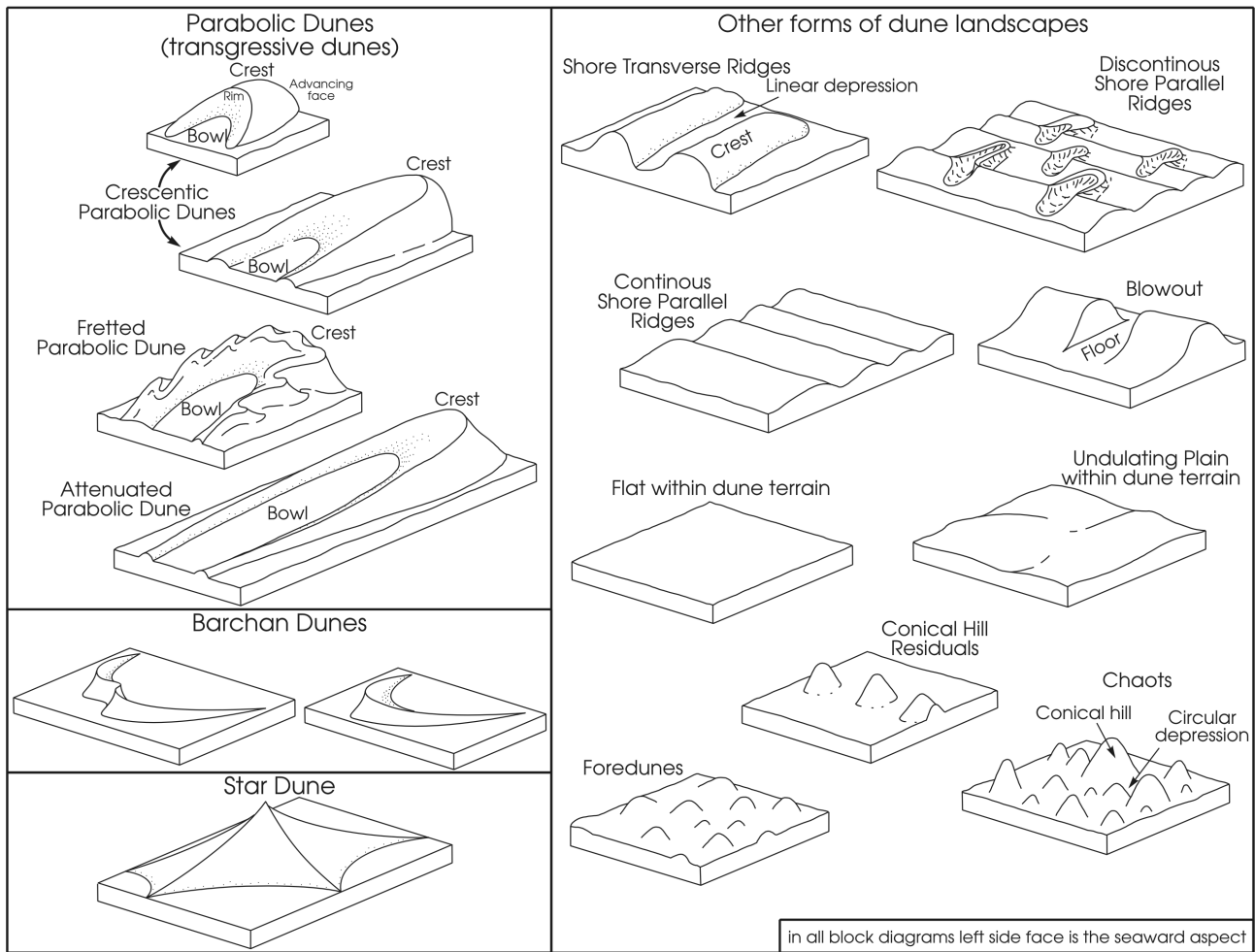


Figure 2. The variety of dune landscapes within which dune slacks can be developed (modified from Semeniuk *et al.* 1989, and with addition of star dunes and barchan dunes). The lowlands in all these dune landscapes, if they intersect the water table, can potentially develop dune slacks.

slack generated *in situ* sediment and this has determined the variation in hydrological style. In addition, there are slacks which owe their wetness to surface or near surface perching or ponding of rainwater, not on intra basin fills generated *in situ*, but on basements and pavements underlying the dunes exposed by wind deflation.

Dune slacks in the Netherlands and Britain are maintained by fresh to brackish water, but groundwater in other climatic zones may not be fresh. When slacks were described in arid coastal dunes settings in the north of Africa and the Middle East, as having mesosaline (sea water concentration) to hypersaline waters, many scientists responded by implicitly excluding these wetlands from the definition of dune slacks. Similarly, dune slacks, which are permanently inundated, and consequently deeper, have been alternately termed dune lakes or lagoons, depending on their stage of development. This has been the case even when the slacks are maintained by the rise in the regional water table. Therefore it must be deduced that the seasonality of rainfall and the height of the groundwater rise are important hydrological criteria for dune slacks.

Dune slacks may be acidic or base rich, as determined by their groundwater and sediment chemistries, but are generally nutrient poor. The short development period,

constant shifting or infilling of the basins in a dynamic dune environment, and the low density and productivity of plants, generally result in lack of organic matter accumulation in the basins.

Where dune slacks are well developed, they are often subdivided on the basis of the underlying parent material, either relatively acidic siliceous sands, quartzose calcareous sands with 1–5% carbonate, or calcareous sands with up to 95% carbonate content (Table 1). Where mixed quartzose/calcareous sand is present, the calcareous component of the sand is often minimal to begin with, and in this type of setting, decalcification has been shown to quickly reduce the amount of calcium carbonate (Tansley 1949; Ovington 1951; Salisbury 1952; Ranwell 1959; Carter & Wilson 1988; Moreno-Casasola 1988; van Dijk & Grootjans 1993; Grootjans *et al.* 1996; Crawford & Wishart 1966; Munoz Reinoso 2001; C A Semeniuk 2007).

The presence of calcium carbonate in the groundwater and in the underlying sediment results not only in a unique style and rate of sedimentation but also in a chemical environment which determines the unusual biotic response of rare flora and inter-annual variation in species composition (Grootjans *et al.* 1998; C A Semeniuk 2007).

Table 1

Examples of dune slack sites with siliceous or calcareous parent sands

Location	Dune slack parent material
Finland	Siliceous (Hellemaa 1998)
Lista & Jaeren (Norway)	Siliceous (Lundberg 1993)
East and west Frisian islands (Netherlands)	Siliceous (Westoff 1989)
Sands of Forvie, Aberdeenshire, (Scotland)	Siliceous (Boorman 1993)
Barry Links (Scotland)	Siliceous (UK Nature Conservation site 2009)
Torr's Warren, Dumfries (Scotland)	Siliceous (Boorman 1993)
Studland Dunes (England)	Siliceous (Chapman 1964; UK Nature Conservation site 2009)
Winterton, Norfolk, (England)	Siliceous (Boorman 1993)
Coto Donana National Park (Spain)	Siliceous (van Huis 1989)
Southwestern Iberian coast, (Portugal)	Siliceous (Freitas <i>et al</i> 2007)
Turner's Peninsula (Sierra Leone)	Siliceous (Scott 1985)
Nigeria	Siliceous (Usono 1985)
East and southeast South Africa	Siliceous (Tinley 1985a)
Zambezi Delta, Maputaland Dunes (Mocambique)	Siliceous (Tinley 1985b; Botha & Porat 2007)
Malaysia Peninsula	Siliceous (Teh 1985)
Eastern Australia (Frazer Is., Newcastle, Myall Lakes, Qld., eastern and western Victoria)	Siliceous (Thompson 1981; Timms 1977, 1982, 1986, 1997; Bird 1985; Outridge <i>et al.</i> 1989; Ward 2006)
West King Island (Tasmania)	Siliceous (Jennings 1957)
Haast Ecological District (NZ)	Siliceous (Dickinson & Mark 1994)
Polonio's Dunes (Uruguay)	Siliceous (Jackson 1985)
Tabasco (Mexico)	Siliceous (Castillo <i>et al.</i> 1991)
Southern Brazil	Siliceous (Cordazzo & Seeliger 1988)
Newborough Warren (Wales)	Quartzose/calcareous sand 1–3 % (Ranwell 1959)
Isle of Man (England)	Quartzose/calcareous sand 2–3% (UK Nature Conservation site 2009)
Noord-Holland (Netherlands)	Quartzose/calcareous sand .05–80% (Rozema <i>et al.</i> 1985)
The Delta (Central & southwestern Netherlands)	< 10% calcium carbonate (van der Meulen & van der Maarel 1993)
Brittany and Normandy (France)	Quartzose/calcareous sand <35 % calcium carbonate (Beeftink 1977)
Magilligan beach ridge plain (Eire)	Quartzose/calcareous sand 11.7–5.5 % calcium carbonate (Carter & Wilson 1988)
Braunton Burrows (England)	Quartzose/calcareous sand (Willis <i>et al.</i> 1959a, 1959b; UK Nature Conservation site 2009)
Cumbria (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Northumberland Dunes (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Sefton Coast (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Kenfig Burrows, (Wales)	Calcareous (Jones & Etherington 1989; Boorman 1993)
Gower, Oxwich, (Wales)	Calcareous (Boorman 1993)
Saltfleetby, Lincolnshire,(England)	Calcareous (Boorman 1993)
Sandscale, Ainsdale, Lancashire	Calcareous (Boorman 1993)
North of Bergen aan Zee (Netherlands)	< 1 % calcium carbonate (Rozema <i>et al.</i> 1985)
South of Bergen aan Zee (Netherlands)	< 15 % calcium carbonate (Rozema <i>et al.</i> 1985)
Flemish coastal plain (Belgium)	Calcareous content frequently 10 % (De Raeve 1989)
Libya	Calcareous sand >90% calcium carbonate (McKee & Ward 1983)
Western India	Calcareous sand >90% calcium carbonate (Skudder <i>et al.</i> 2006)
Alexandria dunefield (S. Africa)	Calcareous sand (McLachlan <i>et al.</i> 1996)
East King Island (Tasmania)	Calcareous sand (Jennings 1957)
Yucatan Peninsula (Mexico)	Calcareous sand (Espejel 1987)

Evolution of slacks further complicates the definition and understanding of the term “dune slack”. Initially, the term carried with it an implication of impermanence. Many individual slacks were short term features lasting between 50 and 100 years, and were replaced during the ongoing processes of dune erosion and sand mobilization, or alternatively by the continual development of spits or beach ridges. However, in some cases, either the progressive infilling did not occur, or the dune slacks became deeper over time, and remained a longer term feature in the landscape. In these wetlands a new sedimentary fill accumulated, such as peat or organic ooze, or carbonate mud, differentiating them from primary dune slack sediments, and generating distinctive geochemistry, hydrochemistry, hydrological processes and plant communities (Schat 1984; Sival 1996; Sykora *et al.* 2004; Grootjans *et al.* 2008). As the wetlands passed through alternate phases of relative humidity and aridity, during the Holocene, the accumulated intra-basin sedimentary deposits began to exert an independent influence on the fluctuating water table, in some cases disrupting the seasonal vertical movement of the groundwater.

To continue this discussion, some examples of dune slacks in unusual settings, or with complex histories or functions are described below, in order to further illustrate the body of diverse coastal dune wetlands which have been described as a “dune slacks.”

Global and Australian case studies

Primarily, and historically, dune slack development and maintenance have been related to coastal processes. The initialization of dune slacks, through reactivation of stabilised dunes due to disturbance and loss of vegetation cover, brings to the fore several important questions regarding dune slack formation and classification. What is the precise meaning of “coastal dune” when applied to dune slacks? Where a sequence of coastal dunes is present, the oldest of which now extend some distance inland, are the wet hollows in all the dunes correctly termed dune slacks? What separates true dune slacks from wetlands occurring within any other type of dune field?

Historically, dune slacks manifest relatively simple hydrological mechanisms and stratigraphic fills. However, what commenced as a dune slack may, if it survives, evolve into a different type of wetland, often with an increase in the internal complexity of features and functions. Straight forward examples include: 1) the accumulation of wetland fills whose composition is sufficiently distinctive from the original dune slack to influence geohydrological processes and geochemical reactions; and/or 2) basin deepening over time, due to tectonic, hydrological or biological processes, which causes the hydrological regime to shift from seasonal to permanent inundation, or increases the number of mechanisms which recharge the wetland. Evolution may eventually produce a wetland with little in common with what is currently termed a dune slack. Another question relating to time concerns the age of a dune slack. Dune slacks are considered to be recent phenomena, integral to the dominant extant coastal land-forming processes. Once a dune slack becomes

established, when does it become too old or too isolated to conform to the criteria of the wetland group? Several examples are described below.

An example of a complex situation in which there are dune slacks is the Donana National Park, southwest Spain. Donana comprises estuarine, littoral and aeolian systems (Siljestrom *et al.* 1994) which are the result of cycles of coastal progradation interspersed with erosion during the Holocene. The aeolian system, which consisted of wind reworked material eroded from a Pliocene-Quaternary coastal cliff and transported by southeast littoral drift, commenced during the third cycle of coastal history, 2500–1000 years BP (Siljestrom *et al.* 1994; Rodriguez-Ramirez *et al.* 1996). There are two recognizable Holocene dune terrains:

- 1 that characterised by the three older sequences, inland from the coast, comprising stable dunes, the most recent of which has parabolic dune forms and well delineated slacks, and
- 2 that characterised by the two younger sequences located at the coast in the 4 km narrow strip of active shoreline (Munoz Reinoso 2001).

Both sets of dunes contain wetland basins. In the undulating landscape of stable dunes, a rising water table creates “lagunas,” temporary water bodies, when it intersects the topographic hollows. The current active dunes exhibit four well delineated dune fronts with linear wet and dry slacks between them (Siljestrom & Clemente 1990). The slacks are regarded as discharge zones for groundwater from the dunes, and the water tables lie approximately 0–0.5 m below the surface for wet slacks and 2.0 m for dry slacks. The dune slacks were all formed during the Holocene, at the coast, and through similar processes. They are maintained by groundwater and are seasonally inundated or waterlogged.

However, the “lagunas” are no longer directly influenced by coastal processes. The only coastal influence is the receiving of airborne marine salts. Hydrologically, they are recharged by rainfall, runoff and groundwater discharge, but these flows respond to localised topographic features and pathways (Serrano *et al.* 2006). In other words, they are developing independent local catchments and internal recharge pathways, and the trend is towards a more closed and internal hydrological system than the open-ended one in the dune slacks of the active dune terrain.

A similar example occurs in King Island, Tasmania (and, potentially, along any coast where several sequences of dunes occur). In King Island, two groups of dunes have been identified: “Old Dunes” and “New Dunes” (Jennings 1957). Slacks in the bowls of the parabolic dunes are present in both systems, but are better developed and more common in the “Old Dunes”. The reasons proposed by Jennings to explain this distribution are linked to evolution of the landscape. Firstly, the denuded thinner “Old Dunes” (quartz sand dunes) lie close to sea level, facilitating intersection of the land surface with the regional water table; and secondly, development of a slightly semi-permeable layer of iron cemented humic sand known locally as “coffee rock”, a diagenetic product linked to water table fluctuations, perches water in the bowls of the “Old Dunes”, thus effecting wetland development. Neither of

these processes is likely to be associated with young dune slacks.

Holocene dune fields west and east of Esperance on the southern coast of Western Australia provide examples of dune slacks and dune hollows formed in an erosional setting. The Esperance region comprises an inland plain (the Esperance Plain) which, towards the coast, gives way to a terrain of gneissic and granitic monadnocks surrounded by Tertiary and Quaternary sediments, eroded back to form a coastline of granitic headlands and islands interspersed with curved bays (Brocx & Semeniuk 2010). Sand transported along shore is reworked by prevailing winds into massive dune fields of parabolic, star, and barchan dunes, and slacks. The variety of mobile coastal dunes in this region provides opportunity to explore the limits of what constitutes a "dune slack".

At Butty Head, west of Esperance, the coastal dunes are mobile and sparsely vegetated star dunes, comprising yellow quartz sand. Buried soils are exhumed in the bowls of the dunes. In winter, the exhumed soil becomes moist but not saturated sufficiently to form wetlands. Hence, though there are dune hollows, there are no dune slacks. At Esperance Bay, the mobile dunes are underlain by a Holocene stranded higher-level beach deposit cemented as a sheet forming a pavement (at the once higher position of a water table). Locally, the cemented sheet has been breached, forming small mesas, and intervening 1.5 – 2 m deep hollows, exposing the water table. Although the entire dune and wetland complex is in a parabolic dune field, the wetlands are not dune slacks, as they are fixed features in an eroded "limestone" terrain. In the parabolic dunes at Rossiter Bay, the regional water table generally is too deep to initiate development of wetlands. However, near the coast, the bowls of the parabolic dunes intersect water flowing along a subsurface pavement sloping shorewards developed on the sediments of the Plantagenet Group, and becomes seasonally inundated when flow is taking place. The wetlands here overlie an unconformity, and not coastal dune stratigraphy, hence are not dune slacks. At Bilbunya Dunes, at the back of a wide beach, between the chaots or conical hill residuals, dune slacks occur where the freshwater water table is close to the surface. Inland of this chaot dune terrain, there are barchan dunes and star dunes, underlain by white sand with yellow and brown quartz sand at depth, with superimposed bounding surfaces and/or truncation planes between successive dune sequences. The hollows and flats, between the dunes, intersect the seasonal water table perched on the bounding surfaces, creating ephemeral wetlands which can be categorised as "dune slacks".

In each of these examples of dune fields in the Esperance region, the basement under the coastal dunes is different: buried soil; a cemented sheet; slightly muddy yellow sand, a relatively impervious bounding surface; Pleistocene limestone; a laterite sheet overlying Plantagenet Group; sediments of the Plantagenet Group; and unconsolidated beach sand. In each situation, the basement affects aspects of the hydrology, such as the flow of groundwater, the access to it, and its duration, depth, and chemistry. Where dune slacks are developed, the wetland substrates comprise the same material as the parent sand, *viz.* colour mottled, fine, homogeneous, quartz sand, and therefore, sediment storage capacity and

the height of the capillary fringe are generally constant. In each of the dune slacks in the Esperance region, there are differences in the density and composition of the plant cover, reflecting the hydrological effects of the different basements, from compacted to unconsolidated types.

Evolution of dune slacks

Evolution takes place in all landscape features and, in relation to dune slacks, may be expressed in the following ways:

1. evolution of the landform setting,
2. evolution of the geomorphology of the wetland basin itself,
3. evolving number and style of hydrological processes,
4. increasing complexity of the hydrochemistry,
5. changes in composition of the accumulating sedimentary fill,
6. geochemical and diagenetic changes, and
7. changes in nutrient content of the wetlands.

Many of these processes are interrelated and one process can initiate or accelerate a second process which may then cause further inter-reactions. A simple example of this is the plant-induced precipitation of interstitial calcium carbonate cement in the vadose zone, which over time accumulates to become an impermeable subsurface layer. This layer then can perch subsurface infiltrated rainwater which makes more water available to plants, and seasonally saturates the sediment above the layer. Plants respond by increasing their productivity and biomass resulting in accumulation of peat which has a different effect on the hydrological properties of the sediments. Although some aspects of interaction will necessarily be referred to in the ensuing discussion, the aim of this section is to try to isolate each of the more common evolutionary aspects of dune slacks.

The most important evolutionary changes in the coastal dunes landform setting pertain to processes which result in either 1) coastal dunes and dune slacks being displaced from the coast by coastal progradation, or 2) hinterland dunes being intersected by coastal erosion. Progradation of the coast may result in coastal dunes, which formerly supported dune slacks, being cut off and isolated from coastal processes. Active dune formation ceases, and dune stabilization allows other mechanisms to come into play and/or to dominate. Landform stability gives plants the opportunity to change their own chemical and sedimentary environment, and provides an opportunity for diagenesis of intra-basin sediments, changing the ways in which water moves, or is stored within the basin. In this case, what were once dune slacks will become increasingly influenced by internal wetland processes (hydrologic, biotic, and chemical activity) tending towards different types of coastal wetlands. Coastal retreat may result in older stabilised dunes being reworked by waves and wind to become modern coastal mobile dune fields, or in the building of dunes on top of an older landform such as a stabilised dune field, planar plateau surface, or alluvial fan. In these latter examples new dune slacks may or may not be created.

Evolution of wetland basin geomorphology usually involves infilling of wet hollows, or the disappearance of ephemeral wet slacks, that occurs naturally in a dynamic dune environment, but may also involve common geomorphic modification such as a change in basin size or shape. A simple example relates to dune slacks in beach-parallel swales which become partitioned into smaller basins by the development of ingressing small parabolic dunes.

Hydrological change is inherent in dune slack developmental history. Shallow lakes change over time to seasonally inundated basins and, eventually, most become seasonally waterlogged basins. In some cases, dune slacks in the bowls of parabolic dunes begin as seasonally waterlogged or inundated basins and persist over time to become shallow lakes through mechanisms such as a rising, or mounded or perched water table.

The evolution of dune slack hydrology is dependent on two major determinants: climate and the nature of the hydrological changes. Dune slacks occur most typically in temperate settings where water availability determines their depth, size, chemistry, sedimentary fill, and biotic response. If rainfall in a temperate climate were to decrease, the size and distribution of the slacks may change, but the processes which are responsible for dune and slack formation theoretically could continue. Longshore drift, wind deflation, coastal erosion due to storms, and construction of spits, berms, beach ridges, and dunes could still continue to develop and shape dune fields. Dune sequences at Donana National Park and Esperance are examples of this. The major changes to dune slacks in this scenario will relate to hydrochemistry.

If rainfall were to increase over time in a temperate climate, the most common evolutionary changes would result in a rise in the water table, and to the depth and duration of surface water. The abundance of water may increase the density of plants, and the volume of above and below ground plant biomass and, over time, the accumulation of un-decomposed plant material as wetland fill. The major changes in the dune slacks in this situation will also be hydrochemical and geochemical.

Three hydrological changes have been identified which can shift the functions typical of dune slacks towards a more, or less, complex stage of development, or an alternate evolutionary pathway: 1) input of additional water from another source; 2) breaching of a seaward barrier; and 3) a rising, or falling, of the water table. Input of water from another source is most likely to occur through streamflow, deriving from natural fluvial migration, or anthropogenic drainage design stream capture, or channel redirection. A natural and relatively common example is dune building obstructing an estuary or river, and forcing channel switching, or mounding, and seepage, which can potentially increase the normal volume of groundwater in local pockets in downslope coastal areas where the dune slacks are located. In this setting, the additional water may alter the sedimentology, hydrochemistry, and water regime, thus increasing the complexity of the processes and the wetland products.

The second hydrological change listed, that of breaching of the seaward barrier, inundates the former terrestrial wetland, transforming it back to a marine condition, thus reverting to a less complex state.

A rise, or fall, in the water table within what is already a dune slack can be due to regional, local, or intra-basinal factors. For example, a rise, or fall, in the dune slack water table may be 1) part of a regional response to cyclic changes in rainfall patterns, progradation or erosion of the beach, or a changing sea level; or 2) due to a set of environmental conditions within a local area such as impounding of groundwater, local seepage, or the barring of a valley tract; or 3) a response to intra-basinal conditions. Regional changes are likely to have a much broader effect on dune slacks than the increase or lowering of the wetland water table. Climatic and coastal changes are likely to include landform remodeling, changes to sediment distributions and volumes, and changes to the style, cyclicity and dominance of erosional and depositional mechanisms, and therefore, clearly the nature of dune slacks will change. Local changes in the water table may increase or decrease recharge to the dune slacks. The changes to water availability and volume may be large enough to result in evolutionary changes to the dune slack, or small enough to be assimilated into the range of hydrological conditions to which the wetland is tolerant. Changes to hydrology brought about by internal stratigraphic or biotic factors do tend to shift hydrological functions from open regionally dominated dune slack processes to more closed intra-basinal wetland processes. In addition to the hydrological mechanisms of groundwater fluctuation and through-flow, which typify dune slacks, development of intra-basinal sediments and soils and conduits create preferential recharge and flow paths, changes to sediment type which increase or decrease porosity and permeability, and influence wetland hydroperiod, and rainwater perching takes place on surface or subsurface sediment layers.

In a temperate climate, dune slack hydrochemistry can be the derivative of one or more of the following processes: regular input of marine salts; seasonal input of slightly acidic rainwater; throughflow of slightly acidic groundwater from quartz-rich aquifers, or calcium and carbonate-rich waters from calcareous aquifers; and evapo-transpiration. Hydrochemical evolution of a dune slack typically involves a change from seawater to brackish water to fresh water. In a shift to more arid climates, the water deficit and evapo-transpirative regime may concentrate and precipitate salts, potentially leading to evaporite sedimentation and hypersaline ecology. In a shift to more humid climates, water surplus may increase the acidity and nutrient concentrations of groundwater, and deplete any calcium carbonate in the coastal sands underlying the dune slack.

Dune slacks can accumulate a variety of sedimentary fills: calcium carbonate mud (calclutite), gypsum or salt evaporites; aeolian sand of quartz, quartz-carbonate, or carbonate composition, humic quartz sand, organic matter, and mixtures of these sediments. As plant cover increases in density, dune slacks often evolve to become dominantly peat-filled. It is not unusual for dune slacks to change the composition of wetland fill in response to relatively short term increases and decreases in regional rainfall, and so their sedimentary fills can exhibit complex stratigraphy with contrasting compositional layers (C A Semeniuk 2007). The existence of individual dune slacks with such variable sedimentary layers indicates that sediment fills across the range reflect evolving and/or changing dune slack ecology.

Diagenetic overprints on dune slack sediments deriving from groundwater movement and geochemical/hydrochemical interactions between the plants, sediments, and groundwater include: textural changes in the sediment, increased hydration of sediments, leaching of salts and nutrients from the sedimentary profile, removal and transportation of the iron oxide coating to sand grains, dissolution of calcium carbonate, and precipitation of carbonate-cemented sands. Many of these processes are typically found in dune slacks (Grootjans *et al.* 1996; C A Semeniuk 2007). In most cases the effects will be minor, but if diagenetic alteration of the sediment permanently alters the dune slack hydrology, this must be viewed as heralding a new stage of wetland development. Such changes could come about through prolonged waterlogging which could result in changes to the texture and fabric of the dune slack sedimentary fill. The diagenetic alteration of grain size and packing brought about by grain dissolution, and reducing sand sized grains to mud sized grains, would increase the density and altering the packing structure of the sediment. The effect may be sufficient to increase seasonal inundation to permanent inundation. This hydrological change would fundamentally alter the wetland type from dune slack to freshwater dune lake and, also, its subsequent developmental path.

A second example of diagenetic effects involves interstitial precipitation of calcite within the vadose zone of the sediment profile to form a partially or fully cemented impervious sediment layer. Wetland hydrology then can be perturbed in several ways: 1) by prolonging the hydroperiod of the dune slack, 2) by increasing the depth of the surface water inundation, or 3) by moderating the water table fluctuations. The first two responses mimic the effects of a rise in the water table. Under certain conditions, the third response simulates a fall in water level. If seasonal rainfall is relatively low, or its frequency changes, there is the potential that there will be insufficient water to independently saturate the near surface sediments and that the seasonal water table rise will be impeded by the "hardpan", thus reducing overall recharge to the wetland.

Low levels of nutrients in groundwater and sediments characterise many dune slacks. Salts, resulting from evapo-transpiration and plant decay, are often removed seasonally by groundwater infiltration and through-flow, so that there is little buildup in the sedimentary profiles. This constant down-profile leaching and exportation of salts from the dune slack is one of their key characteristics in the United Kingdom and Europe. Dune slacks may be found exhibiting every gradation in geochemical composition of their underlying (dune) sands, from 90% calcium and magnesium carbonate content to < 10 % carbonate content in the surface layers with 90% carbonate content at the base of the wetland fill, to <10 % carbonate content throughout.

Given the basic premise is satisfied, that is, dune slacks form in coastal settings in response to erosion and deposition, sediment transport via littoral drift, beach widening, and wind deflation associated with mobile dune development, climatic effects may be incorporated into the category of dune slacks as variations (*e.g.*, expressed as freshwater *versus* brackish water types). However, when climatically induced changes evolve

to the point where the mechanisms which maintain the slack become independent of the surrounding setting and become dominantly intra-basinal, they can be perceived as having evolved beyond the conditions that support dune slacks. It follows that any fundamental changes to the ways in which dune slacks function hydrologically may effectively be set as one of the limiting factors to delimiting of dune slacks. In other words, dune slacks are coastal dune wetlands which are dominated by external geomorphic, sedimentological, and hydrological processes. At the point where extra-basinal processes are replaced by permanent intra-basinal processes which determine the functioning and development of the wetland, dune slacks have evolved into a separate wetland type.

An expanded view and proposed division of dune slacks

Drawing upon the early literature and the case studies provided, there seems to be several settings, in terms of landform, stratigraphy, and hydrology, in which dune slacks can form, and a multiplicity of dune slack types.

As dune slacks are hollows within a coastal dune terrain, the term has been incorrectly applied to hollows within beach terrains, such as those developed behind spits, ephemeral tidal hollows behind beach cusps or storm berms, or hollows formed during tombolo development as a result of construction by refracted wave trains. Spits, developed at the apex of a cusped foreland or along scalloped beach coasts, create shallow leeward depressions which, with subsequent development of foredunes and beach ridges superimposed on the spit or barrier, and on the stranded plain behind the spit, superficially appear as dune slacks. However, the initial development of the hollow was independent of a dune terrain and therefore requires a separate category of slack. In many cases these features may repeatedly form and be destroyed before conditions become suitable for their preservation.

A second example of a hollow unrelated to dune terrain but sometimes confused with dune slacks are barred marine embayments. Marine embayments can be very deep and are unlikely to be seasonal or freshwater for a long period (even when fully cut off from the sea). They are better categorised as a separate class of wetland.

Although dune slacks are coastal landscape features, coastal dune terrains may not always be linked to marine settings. There are examples of coastal dunes bordering estuaries, large lakes, and "inland seas", and these dune environments may comprise Holocene ephemeral or persistent slacks within a dune, beach ridge, or chaot terrain, seasonally inundated by water table rise, and underlain by Holocene sand derived from nearshore and onshore materials from the estuary, large lake, or the "inland sea". In appearance and function, these dune slacks are indistinguishable from dune slacks bordering marine environments.

In all coastal dune terrains, hollows may be formed in the following ways (Figure 3):

1. dune slacks situated wholly in Holocene coastal dunes, composed of Holocene sands, and subject to Holocene coastal processes (Figures 3A, B, C);

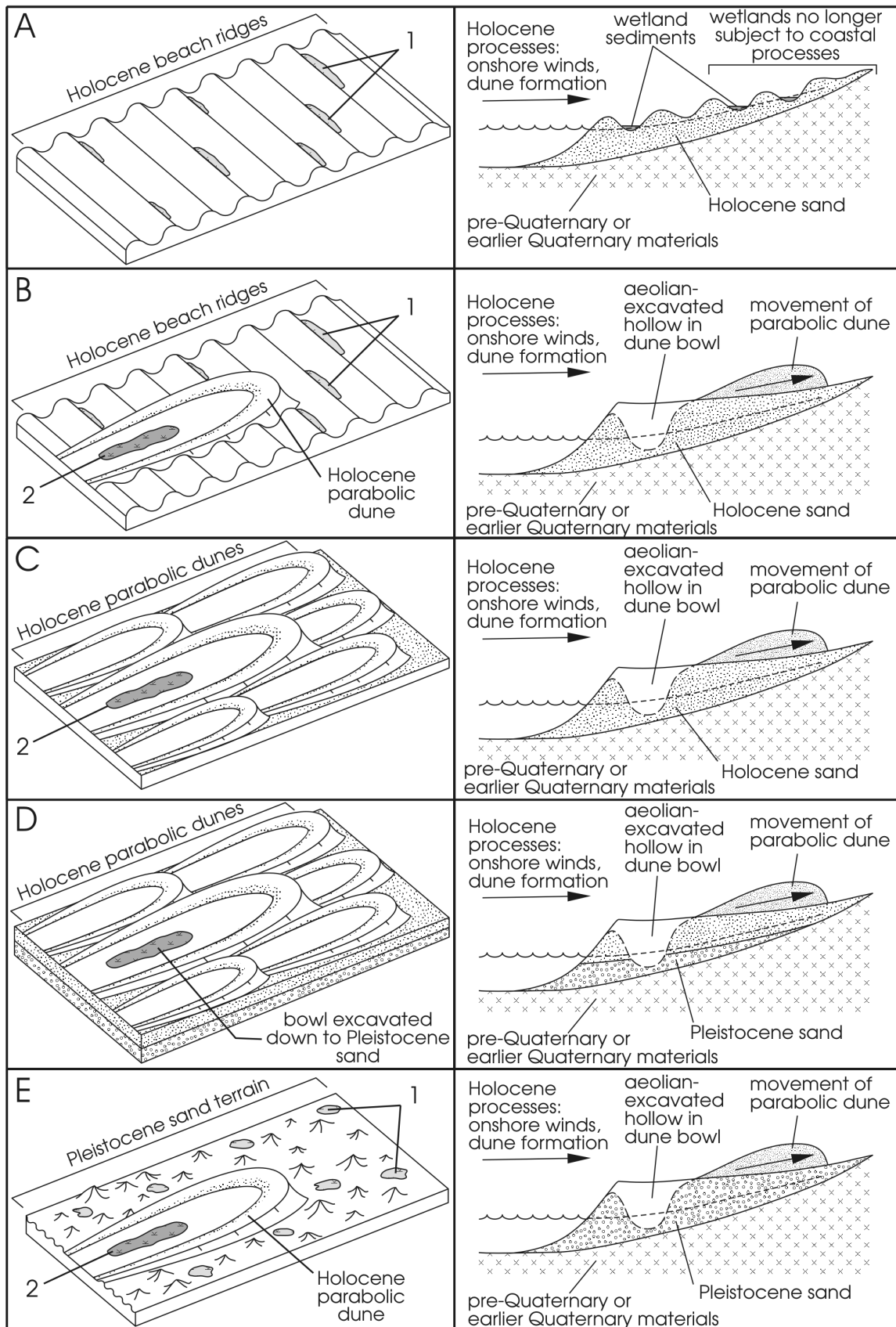


Figure 3. The various landscape and stratigraphic settings for the development of dune slacks, from wholly Holocene sands and Holocene dunes to Pleistocene sands reworked to form Holocene dunes. In all situations, the excavation by aeolian erosion intersects the water table or the zone of capillary rise.

2. dune slacks situated in Holocene coastal dunes, composed of Holocene sands, subject to Holocene coastal processes, on a Pleistocene sand basement (Figure 3D);
3. dune slacks situated in a coastal terrain of Holocene dune landforms, composed of Pleistocene or older sands reworked by Holocene coastal processes (Figure 3E);
4. dune slacks situated wholly in Holocene coastal dunes, such as beach ridge systems, or as chaots, composed of Holocene sands, but no longer subject to Holocene coastal processes (Figures 3A, B – far right).

The idea that dune slacks are wholly Holocene features, as described in Category 1, seems, from the literature, largely to have been assumed, or based on extant processes, rather than investigated radiometrically. It can be seen from this list that subscribing to the above conclusion of dune slacks as wholly Holocene features, in practice, is sometimes difficult to verify. Wetlands in coastal dunes that formed during the Pleistocene, but still function as coastal wetlands today, in a Pleistocene dune terrain, underlain by Pleistocene unconsolidated or cemented basement materials, do not conform to the concept of dune slack, and may be excluded, but there are many examples of coastal dune settings which are more complex. The age of the dune slack becomes blurred where any one of the following conditions are present: 1) there is reworking and mixing of older and more modern sediments, 2) there are ongoing cycles of alternating erosion and deposition of dunes and beach ridges, 3) Pleistocene sediments become exposed to modern coastal processes as a result of coastal erosion and exposure at the coastline and 4) wetland stratigraphic layers derive from both Pleistocene and Holocene coastal processes and diagenesis. Unconsolidated coastal dunes formerly of Pleistocene origin, once again fronting a newly eroding coastline and becoming subject to coastal processes, or reworking of Pleistocene dunes or a Pleistocene pavement, by Holocene coastal processes, provide unconsolidated materials suitable for the current formation of dune slacks.

As a result of the above discussion, it is suggested that Categories 2 and 3 be included as dune slacks. Category 4 is excluded from dune slacks.

Wetlands situated wholly in Holocene coastal dunes, composed of Holocene sands, but no longer subject to Holocene coastal processes are more difficult to ascribe to the original definition and meaning of dune slacks. There exists a boundary which separates incipient and early stage dune slacks from older dune slacks which have become more permanent wetlands, and developed additional mechanisms to sustain them.

Dune slacks, separated geographically from the coast by ongoing progradation, become wetland components of a different setting, *i.e.*, an inland setting where the effects of wind are much less, where the water table configuration and contours flatten, and groundwater movement is slowed, creating a context for local, rather than regional, water flows. The older Holocene slacks described by C A Semeniuk (2007) and the older slacks in Donana National Park exemplify this situation and should be excluded as dune slacks.

Similarly, basins formed within a system of ingressing transgressive dunes, removed from the coast, are no longer coastal dunes and hence no longer subject to coastal processes. Transgressive dunes often move over rock outcrops or surfaces which are related to far older materials (*e.g.*, Precambrian rock basements) and whose aquifers have different hydrological recharge, storage, and discharge mechanisms. Wetland hollows in such settings are also excluded from dune slacks.

There are several hydrologic settings in which groundwaters seasonally recharge coastal dune wetlands (Figures 4 and 5):

1. a seasonally fluctuating water table under a simple prograded beach ridge plain or dune field (Figures 4A and 5);
2. local mounding of the water table under dune topography (Figure 5);
3. local mounding of groundwater behind coastal dunes caused by the barring of a stream, normal to the barrier (Figure 4B);
4. local mounding of groundwater behind coastal dunes that impede the regional groundwater flow, resulting in discharge at the base of the dunes at their seaward edge (Figures 4C, D);
5. groundwater perched on a Holocene impermeable surface underlying the coastal dunes (Figure 5);
6. surface water perched on a Holocene impermeable surface underlying the coastal dunes;
7. surface water and/or groundwater perched on a Pleistocene or older impermeable surface underlying the coastal dunes; and
8. perching on an impermeable layer formed intrabasally by wetland processes.

The hydrologic situations listed above can be amalgamated into three broad groups: 1) unconfined seasonal groundwater fluctuation which causes the water table to intersect the ground surface, 2) seasonal groundwater mounding, and 3) seasonal perching of rain water or shallow groundwater. The traditional view of dune slack hydrology is that of the rising and falling of the regional water table due to its seasonal recharge by rainfall. However, localised water tables can be elevated above the regional water table through local mounding. Groundwater mounding may have the effect of inundating or waterlogging dune hollows which otherwise would be above the level of the regional water table. Categories 2–5 satisfy the classical view of water table rise. Perching or channelling of rain or groundwater, along a Holocene or older impermeable surface underlying the coastal dunes (categories 6, 7), is not comparable to raising the water table by local mounding. In some situations the bowl of the dune is excavated to a water table above the perching layer that is still within the dune terrain and its stratigraphy. In other situations, the bowl of the dune may intersect the underlying pavement or surface of a much older geological formation and, as such, exposes water directly perched on the hardpan. In the former situation the dune slack hydrology is equivalent to Category 2. In the latter situation, wind may expose the water that is directly on the hardpan or perching layer in the dune bowl, but during dry periods it cannot excavate any deeper, showing that the hard

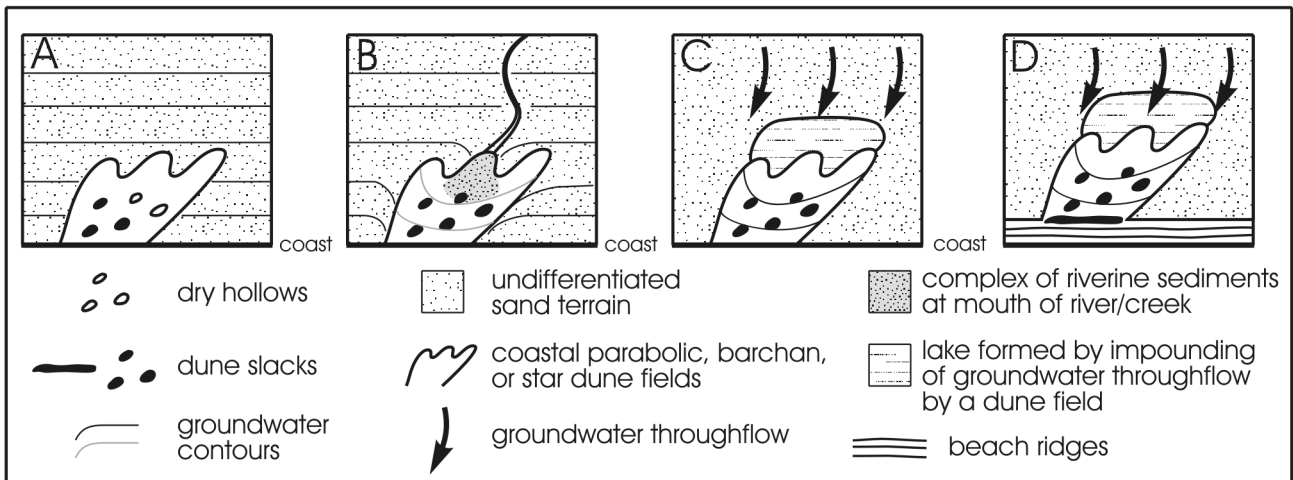


Figure 4. Idealised diagram showing dune fields ingressing inland with variable development of dune slacks. A. Simple dune field in a terrain with seaward sloping water table. B. Dune field in the path of a creek or river that has mounded the groundwater under the dunes so that the aeolian excavations intersect an “elevated” water table. C. Dune field in the path of a major zone of groundwater discharge, impounding the groundwater flow, creating a lake, and causing groundwater to mound under the dunes, so that the aeolian excavations intersect an “elevated” water table. D. Dune field in the path of a major zone of groundwater discharge, impounding the groundwater flow, creating a lake, and causing groundwater to mound under the dunes, so that the aeolian excavations intersect an “elevated” water table, and the elevated groundwater discharge at the interface, between the erosional dune field and the prograded beach ridges, creates a linear dune slack.

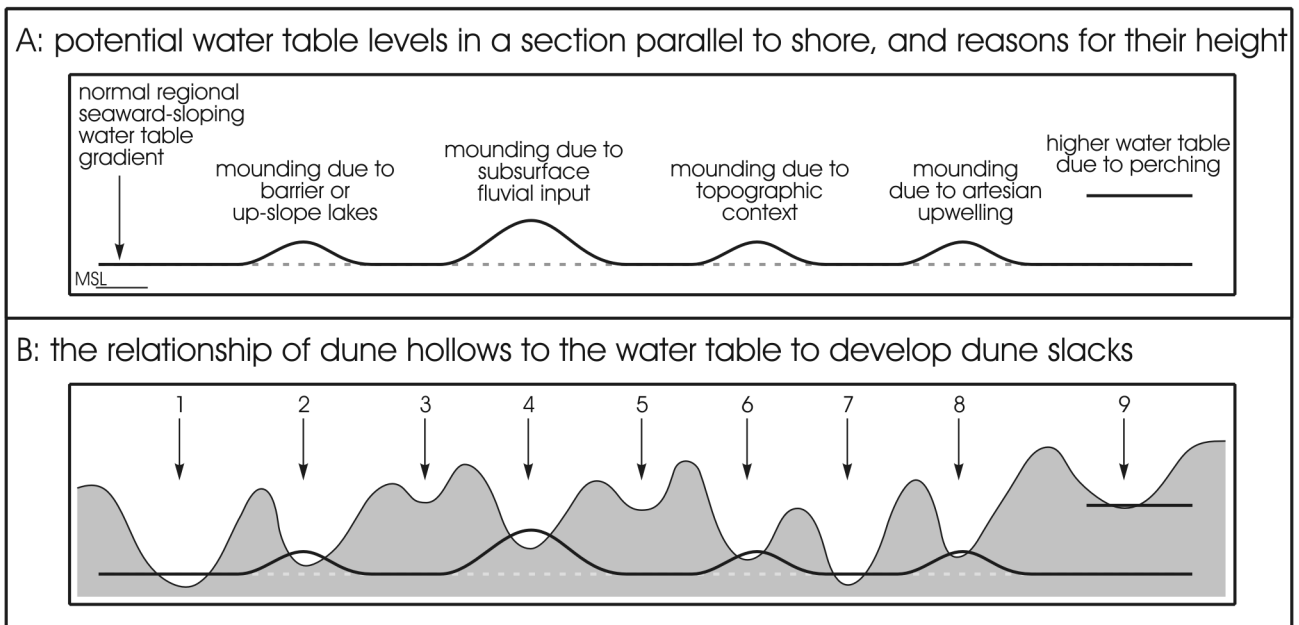


Figure 5. The settings for dune slacks hydrologically and geomorphologically. A. Possible levels of the water table under coastal dunes due to six different hydrological situations. B. Dune landscape superimposed on the water table configurations of (A) with varying intersection of the dune landscape by the water table: 1 and 7 – dune bowl intersects the regionally seaward-sloping water table; 2, 4, 6 and 8 – dune bowls intersect various types of mounded water table; 3 and 5 – dune bowl does not intersect the water table; 4 – dune bowl intersects another type of mounded water table; 9 – dune bowl intersects a perched water table.

layer is not part of the dune dynamics. Categories 6 and 7 thus do not satisfy hydrological criteria for dune slacks. The situation, however, becomes more complex when it is the dune slack itself which generates a hardpan layer which retards vertical groundwater movement. The process described in Category 8 indicates that the wetland has now developed intra-basinal features which alter the basin hydrology to the extent that it is no longer a dune slack.

If the cut-off points discussed above are accepted, then the following description of dune slacks may provide a clearer meaning and scope for the term. The conclusions of this review and discussion are that:

1. dune slacks are wet hollows formed in coastal dunes and not inland dunes;
2. dune slacks differ from other coastal dune wetlands (such as dune-impounded fluvial

- systems) in that they are formed by Holocene coastal processes;
3. dune slacks can form in an erosional or depositional dune or beach ridge setting;
 4. dune slacks are subject to regional geomorphic, hydrologic and sedimentary processes;
 5. dune slacks are subject to seasonal inundation or seasonal waterlogging;
 6. dune slacks are maintained hydrologically by rainfall and groundwater and not by marine or fluvial processes;
 7. dune slacks include the full range of water salinities from freshwater to hypersaline;
 8. dune slacks can evolve from beach slacks;
 9. dune slacks can evolve to other coastal wetland types (at Donana National Park in Spain, and the Becher Cuspate Foreland in Western Australia);
 10. diagenetic alteration of sediments is one of the primary ways that dune slacks can evolve; and
 11. geochemical changes or increase in nutrient content alone should not constitute criteria to change classification from dune slack to coastal wetland.

Some form of amended classification may be useful in separating and organising the different types of wetlands currently recognised in the category of dune slacks. Recognition of the variety of settings, geomorphic and hydrologic processes, and internal sedimentary, hydrochemical and geochemical interactions, occurring within dune slacks, has expanded the numbers and types of wetlands in this class. For purposes of conserving the full range of types, a simple subdivision is proposed here.

There are four coastal dune settings where dune slacks may form: marine, estuarine, large lakes, and "inland seas". Within these settings, there are two subdivisions of dune slacks: alpha types (α), formed in a depositional setting behind foredunes and beach ridges, and beta types (β), formed in an erosional setting between the arms of parabolic or star dunes, in the inter-dune depressions of a barchan dune field, and in and around conical dune residuals (the prefixes α and β are proposed in this paper to distinguish the two types). For β dune slacks, in Western Australia, wind erosion is most effective on dry sand during summer, when excavation may continue to the summer low water table level. With winter rainfall recharge, water tables rise above, or saturate the basin floor, to produce seasonally inundated or waterlogged basins, respectively. Descriptors used in other wetland classifications can also be used to further subdivide dune slacks, *e.g.*, saline, calcareous, acid, organic rich, or vegetated.

The regional factors in Western Australia important for development of dune slacks

In Western Australia, the regional factors important in the initial development of dune slacks and in their evolutionary pathways are:

1. geological/stratigraphic setting
2. Quaternary coastal setting
3. sand supply

4. coastal wind regime
5. climate
6. coastal sand composition
7. hydrology
8. biogeographic setting

The geological/stratigraphic setting of the coast is a critical factor in determining whether coastal dune fields, and hence dune slacks, develop. Geological setting, such as a tectonically active region where uplift exposes rocks to form extensive cliff shores, or where ancient bedrock is exposed, will determine coastal form and preclude slack development (Semenuik *et al.* 1982; Semenuik 2008; Brocx & Semenuik 2011). For example, dune fields (and dune slacks) are not developed along the cliff shores of the Kimberley Coast, the rocky shores of the western Dampier Peninsula, the rocky shores of the Dampier Archipelago, the rocky coastal tract between Cape Range and Cape Quobba, the limestone rocky shores between Dirk Hartog Island, Zuytdorp Cliffs to north Kalbarri region, the cliffed red sand terrain of Peron Peninsula (Shark Bay), the sandstone rocky shores of the Kalbarri region, the coast of the Leeuwin Ridge, and the limestone cliffs bordering the Nullarbor Plain (Figure 6). The sandy shore of the coastal Perth Basin has numerous coastal dune fields but, here, stratigraphy plays a role in whether there are dune slacks. The Quaternary coastal stratigraphy of the Perth Basin is generally Holocene sand (dunes) perched on or encroaching upon Pleistocene limestone, so that the coast comprises either a limestone cliff, or a dune field perched on a limestone "plateau". Aeolian erosion in such dune fields excavates hollows down to the underlying limestone and not to a water table. Where there are cusped forelands, there is scope for mobile dune fields *and* for development of dune slacks. The southern coast of Western Australia has massive dune fields and dune slacks because it consists of Precambrian rock headlands and intervening connective dune barriers.

Quaternary coastal setting also determines whether dune fields and dune slacks are developed. The main Quaternary coastal settings in Western Australia are (Figure 6):

- deltas and tidal flats of the Cambridge Gulf, Kimberley and King Sound regions (Semenuik 1993; Brocx & Semenuik 2010, 2011; Semenuik 2011; Semenuik & Brocx 2011);
- barrier dunes and barrier limestone and tidal flats of Canning Coast (Semenuik 2008);
- deltas, limestone barrier coasts, beach/dunes shores and ria/archipelago coasts, and extensive tidal flats of the Pilbara Coast (Semenuik 1996);
- the delta complexes of the Gascoyne Delta (Johnson 1982) and Wooramel Delta (Logan 1970);
- the tidal flats and prograded seagrass complexes of Shark Bay (Logan 1974);
- the beach ridge plains and cusped forelands of the Rottne Shelf Coast (Searle & Semenuik 1985);
- the Scott Coastal Plain shore;
- the barrier dune complexes of the south coast (Brocx & Semenuik 2010; Semenuik *et al.* 2011); and
- the dune accumulations between Israelite Bay and Eucla on the south coast.

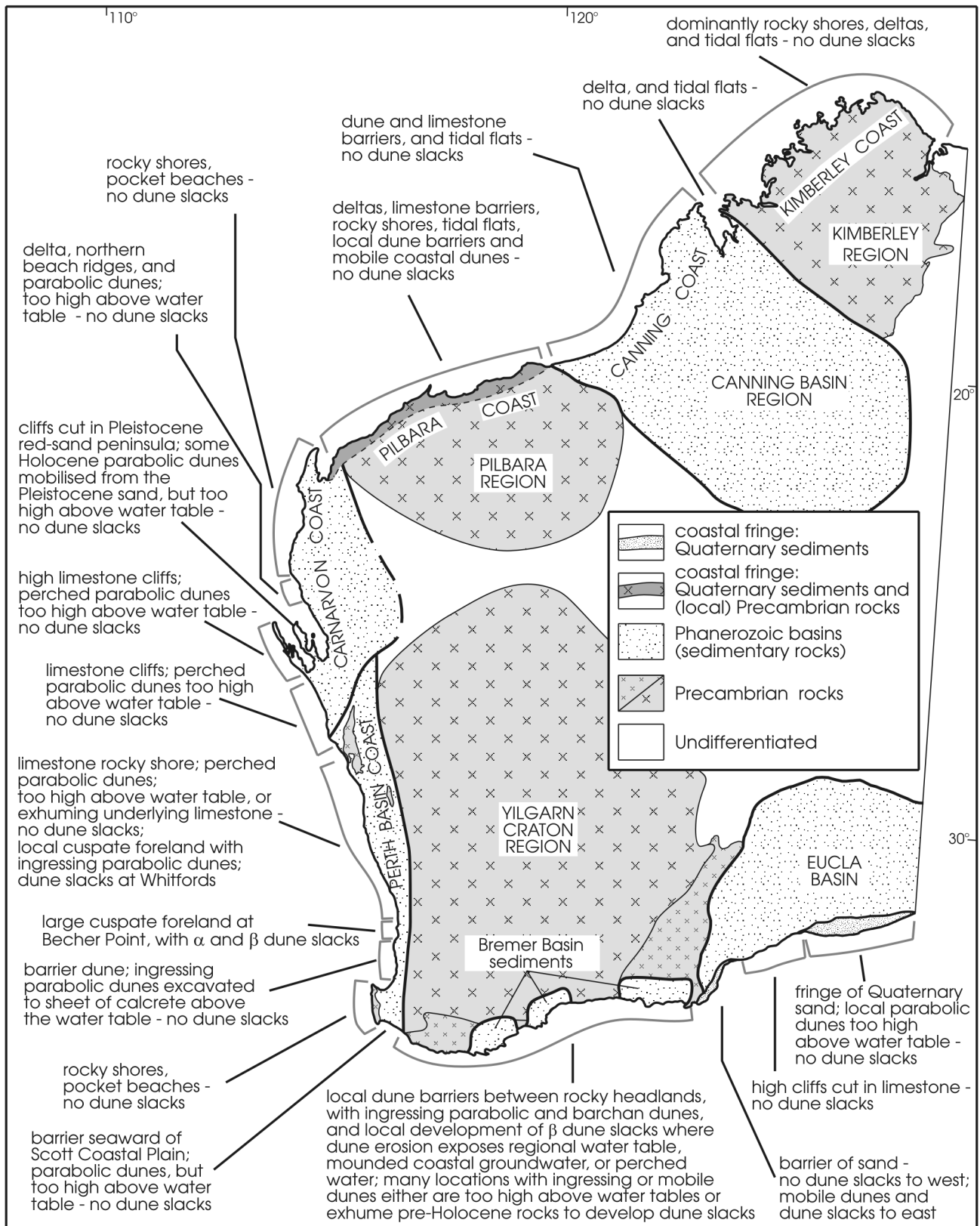


Figure 6. The Western Australia coast, showing its geological framework, the various sectors where different types of coasts are developed, the sectors where coastal dunes are developed, and where dune slacks are developed.

Tidal flats and deltas generally do not support massive coastal dunes and associated slacks. The main areas of Quaternary deposits where dune fields may develop are the beach ridge plains and cusped forelands of the Rottnest Shelf Coast, and the coastal complexes of southern Western Australia (*cf.* Pye 1983).

Sand supply is critical to the development of coastal dune fields. Alongshore and onshore transport, erosion along the coast, and biogenic generation of sand in near-shore seagrass banks, supplies sediment to the shore (Searle & Semeniuk 1985, 1988; Searle *et al.* 1988; Semeniuk & Searle 1986). Massive dune fields, barrier dunes, and prograded beach ridges and dunes are developed in the following localities along coastal Western Australia: northern Dampier Peninsula, with reworking of Pleistocene sand into northerly shore transport (Semeniuk 2008); the dune barriers along the Canning Coast, with reworking of Pleistocene sand (Semeniuk 2008); Tubridgi Point (north-eastern Exmouth Gulf) with reworking of delta sand and red desert sand; the Bejaling Beach Ridges of the northern Gascoyne Delta (Johnson 1982); various cusped forelands, beach ridge systems, and perched dunes along the coast of the Rottnest Shelf (Searle & Semeniuk 1985; Semeniuk *et al.* 1989), with reworking of Pleistocene quartz sand, erosion of Pleistocene limestone, biogenic generation from local seagrass banks, and alongshore transport from southern sectors (Searle & Semeniuk 1985); the coastal edge of the Scott Coastal Plain, with reworking of Pleistocene quartz sand; and the barrier dunes and perched dunes developed between and on rocky headlands of the south coast, with reworking and alongshore transport of Pleistocene quartz sand.

Once emplaced on the coast, sand is subject to the coastal wind regime and, depending on the wind's intensity, duration, direction, and season, it is mobilised into land-ingressing dune fields (Semeniuk *et al.* 1989). Sand mobility is most efficient in summer, when sea breezes intensify and sand is dry. The most intense winds in Western Australia in many locations are along coasts that are rocky shores, limestone shores and limestone terrains, and hence do not result in massive dune fields – the Pilbara Coast and the Shark Bay areas exemplify this. Strong winds, resulting in inland-ingressing dunes are located between Dongara and Bunbury on the west coast, and along the south coast. For the west coast, wind intensity increases northwards, and changes from westerly to south-westerly to southerly, and the dunes tend to be perched on Pleistocene limestone (as noted above). For the south coast, there are numerous ingressing dunes, with the majority perched on Precambrian rock, Tertiary plains, or Pleistocene limestone.

The coast of Western Australia, from north to south, has climates of Tropical humid, subhumid, semiarid, arid, and Subtropical arid, semiarid, subhumid, and humid. Along the south coast from west to east climate spans Subtropical/Temperate humid, subhumid, and semiarid. Mobile dune fields with dune slacks occur in climates of Subtropical subhumid, and Subtropical/Temperate humid, subhumid, and semiarid, with rainfall as low as 300 mm/pa and as high as 1400 mm/pa. In contrast, dune slacks in coastal United Kingdom and northern Europe are located in a Temperate oceanic climate (Trewartha

1968) with rainfall *circa* 750 to 1000 mm/pa – as such, they are situated in a relatively consistent maritime climate and biogeographic setting, and broadly have responded similarly in terms of landforms, soil development, geochemistry/hydrochemistry, and ecologic succession. Thus there is a wider range of climate zones for dune slacks in Western Australia, which have effects on vegetation biogeography and biodiversity, development of wetland sediments and soils, and diagenesis.

Spanning a large latitudinal range, and crossing a number of geological regions, coastal sands in Western Australia show a range in composition, from carbonate-dominated to quartz-dominated, and variably feldspar-bearing (Searle & Semeniuk 1988; Semeniuk *et al.* 1989), with variation reflecting local provenance such as seagrass banks, erosion of onshore materials, riverine input, or alongshore transport. In local areas, there also may be a strong component of opaque and heavy minerals, such as rutile, ilmenite, tourmaline, apatite, magnetite, amongst others (Baxter 1977). In the United Kingdom and northern Europe, initially carbonate-bearing dune slacks, with acid groundwater, undergo dissolution of carbonate, geochemically evolving from quartz-and-carbonate sand to quartz-rich sand, reflecting levels of "geochemical maturity" or "pedogenic maturity". This has been an important part of their dune slack evolutionary processes, with major effects on vegetation. However, in Western Australia, the compositional variation of coastal sands is such that the parent sands may be quartz, a calcareous/quartzose mix, calcareous, or containing opaque and heavy minerals. Some of these parent sands are at a compositional level that would be considered as "mature carbonate-depleted sand" in the United Kingdom and northern European dune slacks. Further, with the opaque minerals and feldspar in the sands of coastal Western Australia, there is a degree of geochemical diversity, in the inherent content of Fe, P and other elements, not recorded as present in dune slacks of the United Kingdom and northern Europe. In this context, dune slacks of Western Australia need to be described in terms of evolutionary pathways and geochemical pathways as systems distinct from existing models overseas.

Hydrological conditions required for dune slack development are seasonal rainfall and groundwater rise. On the western and southern coasts, winter rainfall recharges the groundwater in unconfined sandy aquifers and, as such, groundwater is fresh. Along the western coast, groundwater resides in calcareous sand, calcareous and quartz sand, or quartz sand and is carbonate enriched. On the southern coast, groundwater resides in mainly quartzose sand, and is carbonate-depauperate. The water table on which dune slacks are developed may underlie dune terrains in a number of configurations (Figure 5), *viz.*, a seaward sloping unconfined ground water table as part of the regional gradient; locally mounded groundwater; and perched groundwater (though not perched directly on rock or a hardpan).

Biogeographic setting is also an important factor in the evolution of dune slacks. In Western Australia, the coastal systems with dune slacks cross several biogeographic zones (Hopper 1979; Thackway & Cresswell 1995; Myers *et al.* 2000; Hopper & Goia 2004). The dune slack plants and other biota, that evolve from simple to more complex

systems, are specific to the biogeographic setting. Dune slacks in semiarid/arid regions may support fewer species of rushes and sedges, whereas those in humid regions initially support a higher diversity of rushes and sedges and quickly give way to complex vegetation associations.

Dune slacks in Western Australia

In Western Australia, dune slacks have been identified in six regions. From north to south, they are: Whitfords and the Rockingham-Point Becher area on the west coast, and Meerup chaots and Yeagarup barrier dune, Reef Beach area (south of Moates Lake, east Albany, Warramurup dune field (near Bremer Bay), and Bilbunya, east of Israelite Bay on the south coast (Figure 7). A description of the dune slacks follows. Data on rainfall, dune sand grainsize, dune slack grainsize and sediment type, and water salinity and pH for the various dune slacks are presented below. Maps of the dune slacks, aerial photographs, and wind rosettes for various sites are shown in Figures 8–13. Details of substrate geochemistry/mineralogy, the opaque/heavy mineral component of the dune sands and dune slacks (variable along the coast, both regionally and locally), and the hydrochemical and pedogenic evolution of dune slacks are beyond the scope of this paper and will be presented in a later study.

Whitfords

The dune slack at Whitfords is a seasonally waterlogged basin located on a Holocene cusplate foreland (Semeniuk & Searle 1986) in a subtropical subhumid climate with rainfall of ~ 870 mm per annum. It is a β dune slack in a swale behind the foredune. Sand surrounding the dune slack is fine to medium grained quartz-calcareous (40–60% CaCO_3). The slack is underlain by a thin layer (< 1 cm) of calcilutite. Dune slack water has salinity of 900 ppm, a pH of 7.3–7.9, and is oligotrophic. The dune slack was vegetated by low coastal heath and *Lepidospermum gladiatum* sedge.

Point Becher area

The dune slacks of the Point Becher area are located on a cusplate foreland (Figure 8) in a subtropical subhumid climate with rainfall of 822 mm per annum. Several types are present: α dune slacks situated in swales of beach ridges at the western and youngest part of Point Becher; barred marine lagoons evolved to become freshwater dune slacks; and β dune slacks in the bowls of parabolic dunes and chaots (C A Semeniuk 2007). They have all been subject to water table rise following coastal progradation and stranding and are freshwater systems (C A Semeniuk 2007). Dune sand in the region has 30–40% CaCO_3 , and is fine to medium grained. Dune slack water has salinity of 50–400 ppm, a pH of 7.1–8.3, and is oligotrophic.

Dune slacks in the swales between beachridges exhibit groundwater throughflow and experience coastal processes. The youngest dune slack is seasonally waterlogged, and underlain by calcareous sand, humic sand, and calcilutaceous muddy sand. Slightly older slacks are seasonally inundated, and underlain by thin calcilutite (10–20 cm) and calcilutaceous muddy sand. They are vegetated mainly by sedges *Baumea juncea*,

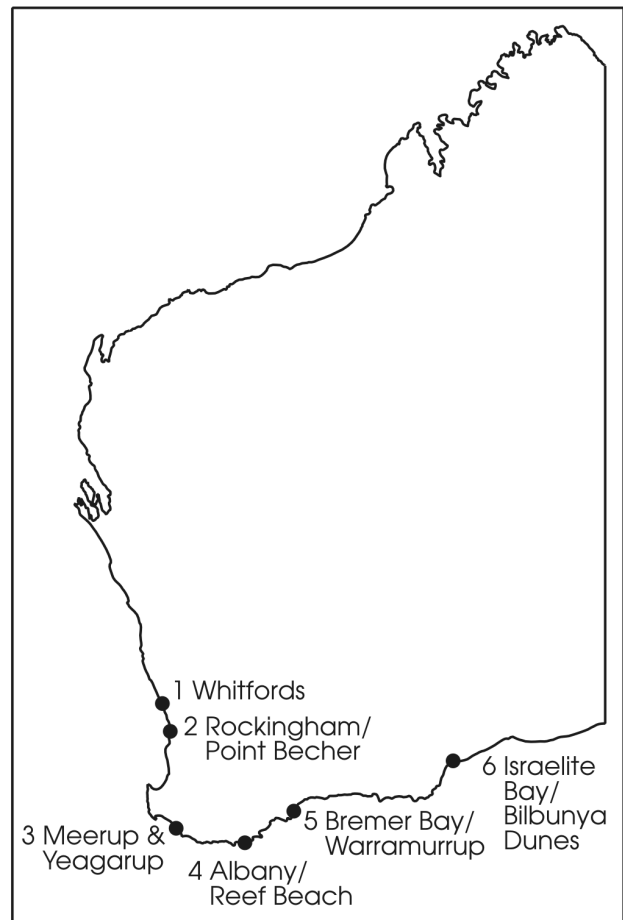


Figure 7. Location of dune slacks in Western Australia

Lepidospermum gladiatum, and *Ficinia nodosa*, and older slacks exhibit herbs *Centella asiatica* and *Lobelia alata*.

The former barred lagoons still retain evidence of spit development within their basins. They are seasonally inundated, underlain by thin calcilutite (10 cm) and organic-matter-enriched calcareous sand, and vegetated by rushes *Juncus kraussii*, herbs *Samolus repens*, and scattered low coastal shrubs *Halosarcia halocnemoides*. Hydrology and hydrochemistry now are mainly freshwater, but the seaward barrier to the most seaward wetland is intermittently breached and the wetland, for a short time, becomes brackish.

At Secret Harbour, β dune slacks are in the deflated bowls of northeasterly oriented parabolic dunes within an erosional setting of mobile sand sheets and conical dune residuals (Figure 9). The slacks are seasonally waterlogged and seasonally inundated basins, oval to linear in shape, and underlain by freshwater. They are underlain by richly calcareous quartzose sand, humic sand, and calcilutaceous muddy sand. Some slacks are bare, due to the rapidity of infilling and excavation, but others are colonised by herbs, patches of the rush *Juncus kraussii* and various coastal heaths.

Meerup chaots and Yeagarup barrier dune

On the south coast between the Warren and Meerup estuaries, and along the coastal zone eastwards of the

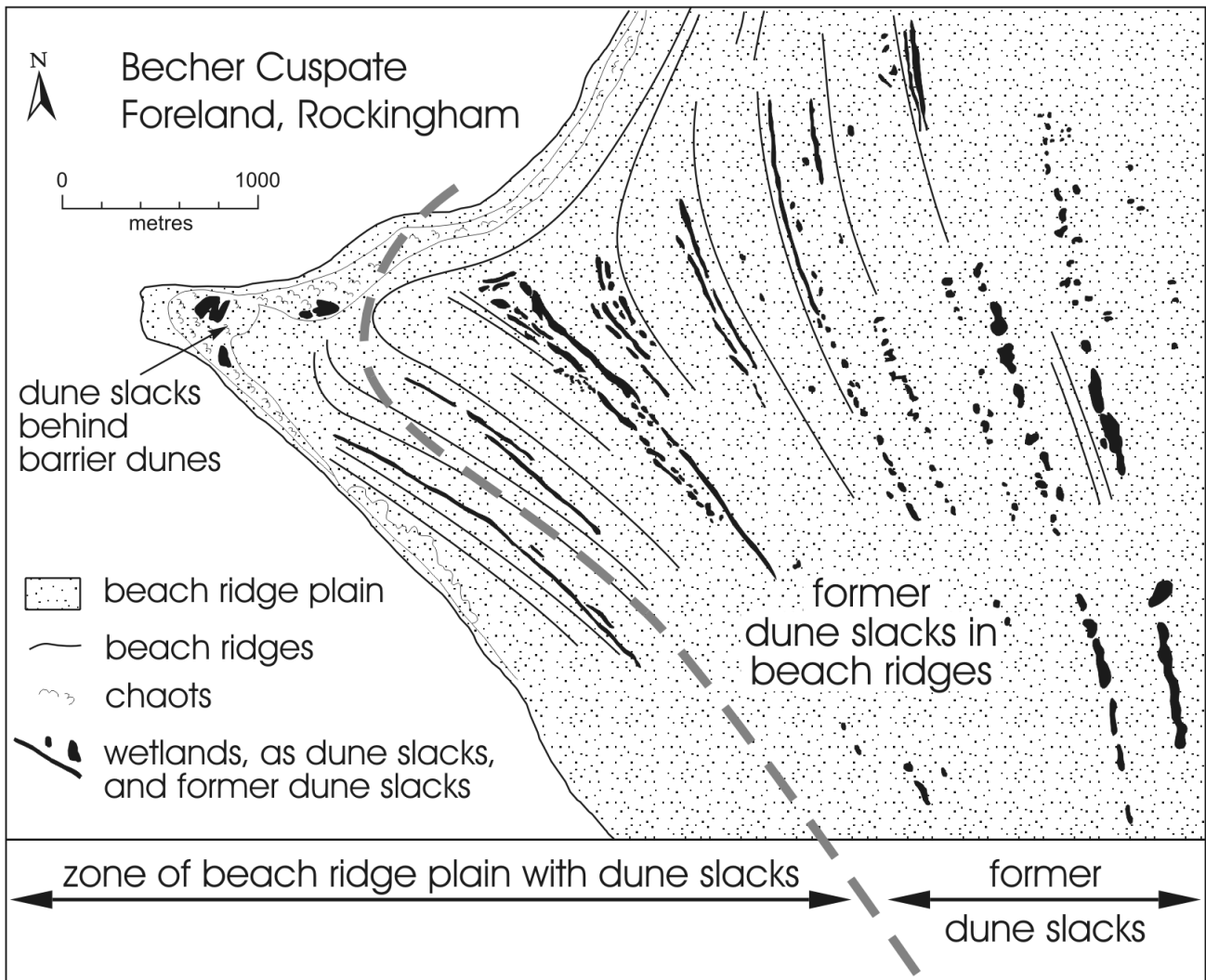


Figure 8. The Becher Point Cuspate Foreland, showing location of α dune slacks in the western and south-western part of the cuspate foreland, and the occurrence of the former α dune slacks in the eastern part of the cuspate foreland.

Warren estuary, in a climate setting of subtropical humid with an annual rainfall of 1400 mm, successive foredunes and aeolian erosion have produced an irregular series of swales, with shore parallel hummocky ridges, depressions, and incipient blowouts (essentially a terrain of chaots), which host numerous microscale to leptoscale, and sometimes ephemeral, seasonally inundated and waterlogged β dune slacks (Figure 10). Dune sand in the chaots has 2.5–5.0% CaCO_3 , and is medium grained. Dune slack water has salinity of 514–675 ppm, a pH of 7.4–8.1, and is oligotrophic. The sedimentary fill of the dune slacks is calcareous/quartzose organic matter enriched sand, and they are vegetated by *Baumea juncea* sedge and *Centella asiatica* herbs.

Landward of the chaot terrain, Holocene parabolic dunes have mounted the onshore limestone ridges creating the massive Yeagarup dune fields, separated from the shoreline, but still subject to coastal aeolian processes, and there are β dune slacks in the bowls (Figure 10). Dune sand in the barrier has 0.5–6.0% CaCO_3 , and is fine to medium grained. The dune slacks are seasonally waterlogged and seasonally inundated

basins, which intersect the groundwater that resides in the dune stratigraphy. Dune slack water has salinity of 34–400 ppm, a pH of 7.8–8.1, and is oligotrophic. They are generally vegetation-free, underlain by bioturbated sand.

Reef Beach dune slacks

Between Moates Lake and Reef Beach, east of Albany, with a climate of subtropical subhumid and annual rainfall of 930 mm, β dune slacks occur in an erosional setting of ingressing parabolic dunes. They are microscale to leptoscale, seasonally waterlogged, irregular basins in deflation hollows, underlain by quartzose sand, and unvegetated, due to their ephemeral nature in this dynamic setting (Figure 11). Dune sand has 12–14% CaCO_3 , and is fine grained. Dune slack water has salinity of 500 ppm, pH of 7.3–7.9, and is oligotrophic.

Warramurrup dune field

Dune slacks at Warramurrup near Bremer Bay, with a climate of subtropical subhumid and annual rainfall of 600 mm, occur in an erosional setting with north east oriented barchan dunes at the back of the beach

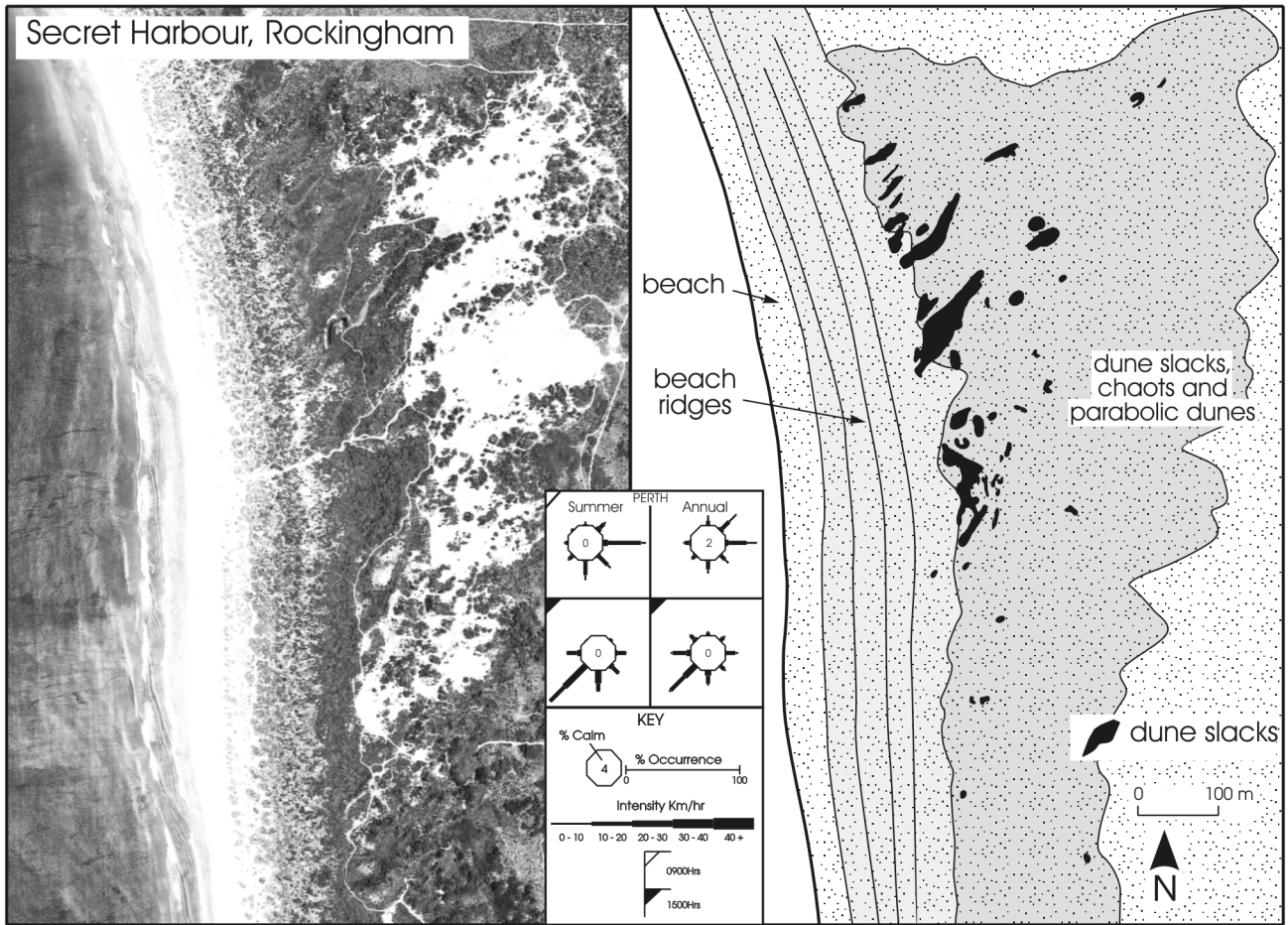


Figure 9. Aerial photography showing the erosional inland ingressing dune field of the Peelhurst Suite at Secret Harbour, and map of the β dune slacks developed in the direction of the prevailing onshore summer winds (see wind rosette inset). The zone of β dune slacks has been separated from the sea by progradation of beach ridges.

(Figure 12). They are microscale, seasonally inundated β dune slacks, which are underlain by quartz sand and are unvegetated. Dune sand has 14–28% CaCO_3 , and is medium grained. Dune slack water has salinity of 160–800 ppm, a pH of 7.0–7.9, and is oligotrophic.

Bilbunya Dunes

The region of the Bilbunya Dunes, with a climate of subtropical semiarid and annual rainfall of ~270 mm, is a complex of β dune slacks (Figure 13). From Israelite Bay to the Bilbunya Dunes, the coast is a coastal plain with high sand dunes and elongated lagoons and the eastern part of the coastal plain is comprised of star dunes, barchan dunes, and chaots. The Holocene coastal dunes are underlain by fine quartz sand and bioclastic calcium carbonate grains, and sheet or nodular calcrete 30–60 cm below the surface (Lowry & Doepel 1974). Dune sand has 1–38% CaCO_3 . Dune slack water has salinity of 40–750 ppm, a pH of 7.4–8.2, and is oligotrophic. The dune slacks form in three areas: between the arms of the star dunes as seasonally waterlogged and inundated basins, between the barchan dunes as seasonally waterlogged basins and palusplains, and between the chaots on the backshore of the beach as seasonally waterlogged and inundated basins. The sedimentary fill is composed of the same

material as the dunes, but some evidence of diagenetic alteration (staining and cementation) is evident. Wind-swept moist palusplains may exhibit a surface of wind-adhesion ripples. Most slacks are bare, but some support herb vegetation.

Former dune slacks in Western Australia

Dune slacks of course evolve and, as noted earlier, if their surrounding terrain is stranded too far from the coast, coastal processes of dune mobility and dune reactivation cease, or intra-basinal wetland processes begin to dominate, such wetlands cease to be dune slacks, or be part of a dune slack environment (Figure 14). In Western Australia, wetlands that were former dune slacks, but have evolved beyond the dune slack stage, occur at Jurien, at Rockingham, on the western dune barrier to Lake Walyungup, Rockingham Plain, Warnbro shore, and Becher Point eastern wetlands, at Busselton, in beach ridge swales, at Prevelly, in dune chaot terrain, and at Albany, in beach ridge swales.

Jurien

Wetlands, that began as β dune slacks in the bowls of

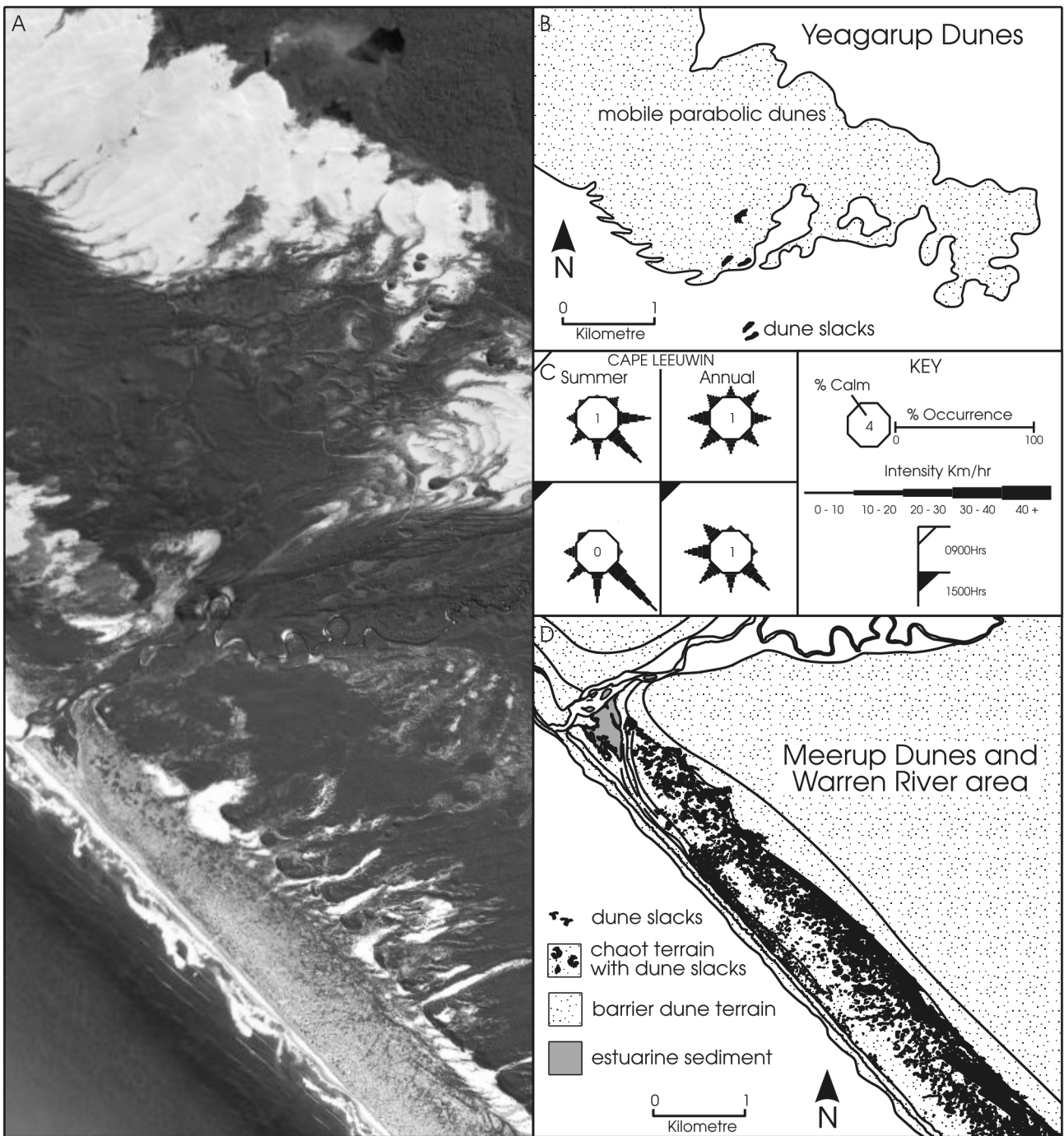


Figure 10. A. Aerial photography showing the Meerup-Yeagarup area. The inland Yeagarup dunes are a massive dune field perched on limestone. B. Location of β dune slacks in the inland Yeagarup dune field. C. Wind rosettes for the region from Cape Leeuwin data. D. The location of β dune slacks in the Meerup chaot dune terrain proximal to the coast.

NNE-trending attenuated parabolic dunes on Holocene sedimentary deposits, are now located in immobile (vegetated) dune terrain, and no longer in the dune slack environment. These wetlands exhibit one of three stratigraphic types: 1) seasonally waterlogged basins underlain by humic sand, depleted of carbonate grains, and vegetated by rushes and sedges, 2) seasonally waterlogged basins underlain by thin calcilutite (< 1 cm), vegetated by rushes, sedges, and low coastal heath, and 3) seasonally inundated basins underlain by

thicker calcilutite (~ 10 cm), vegetated by coastal heath communities with interspersed sedges and herbs. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and those, underlain by thicker calcilutite, also perch rainwater.

Peelhurst Suite western Lake Walyungup

Wetlands that began as β dune slacks in bowls of SW-trending parabolic dunes on the barrier that isolated Lake Walyungup from the ocean are now in fixed (vegetated)

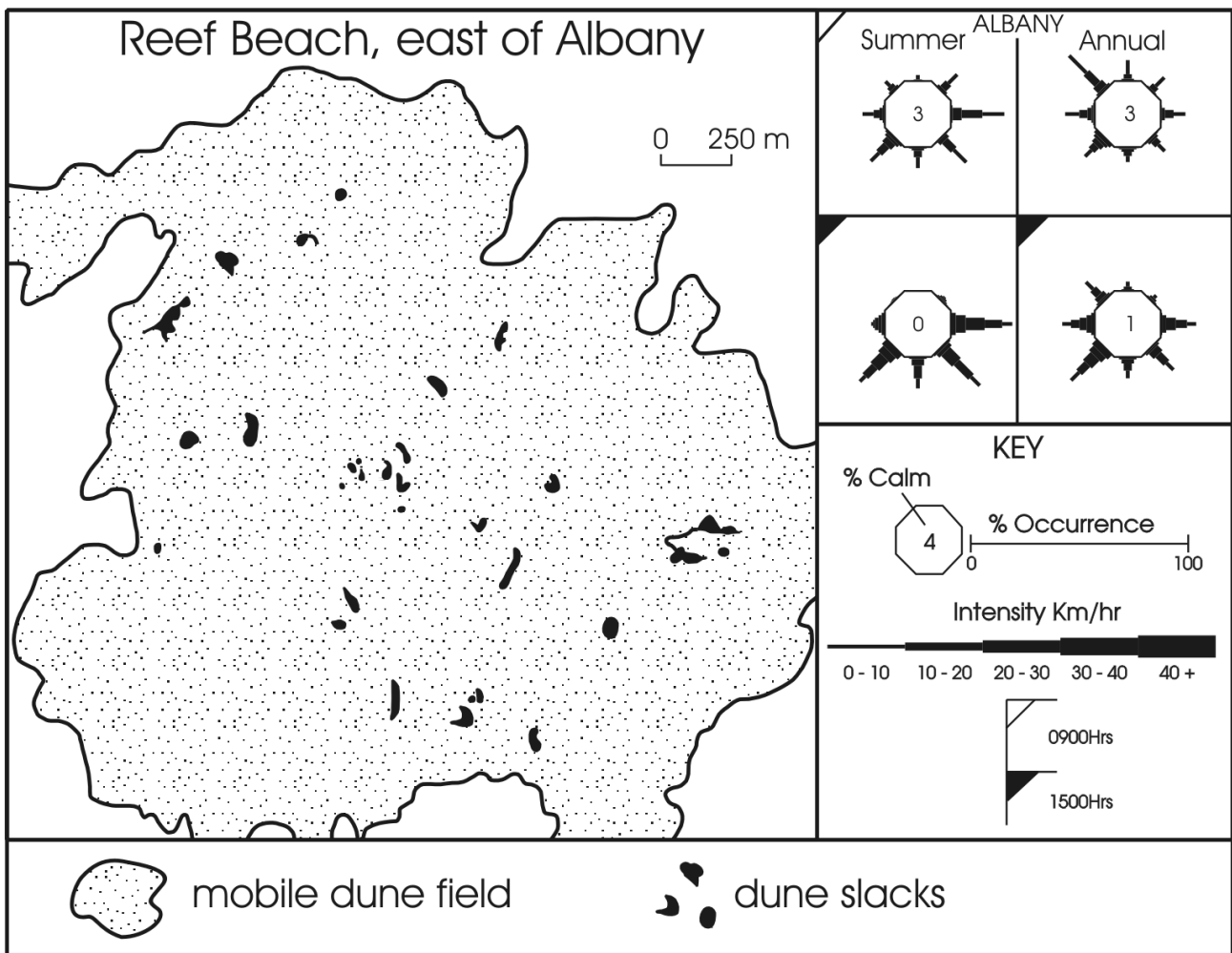


Figure 11. The Reef Beach Dune field east of Albany showing β dune slacks in the mobile dune system. Inset shows wind rosettes for the region from Albany data.

dunes, well inland from the coast. These wetlands are seasonally waterlogged and seasonally inundated basins, which are recharged by seasonal fresh groundwater rise, and perch rainwater. They are underlain by 10–20 cm of calcilutite, and vegetated by rushes, sedges, herbs, and low coastal heath.

Rockingham Plain

Swales of the beach ridge complex, some 6000–5000 years old, of the Rockingham Plain (Searle *et al.* 1988), began as α dune slacks and have developed to the stage that they have ~ 1 m of calcilutite, capped by indurated calcilutite. They are stranded inland, and no longer in the dune slack environment. They are seasonally waterlogged and seasonally inundated basins, vegetated by rushes, sedges, herbs, and low coastal heath. The wetlands are recharged by seasonal fresh groundwater rise, and also perch rainwater.

Warnbro shore

The northern shore of Warnbro Sound, the location of the former Peel Harbour (surveyed by John Septimus Roe in 1839, and re-surveyed by Commander Archdeacon in 1878) that rapidly infilled with coastal sediments during

the period 1839 to 1878 was an area of beach slacks, underlain by calcareous quartzose sand.

Becher Point eastern wetlands

The central and eastern part of the Becher Point cusped foreland, some 4500–1500 years old, has numerous linear, ovoid and circular swale wetlands in the beach ridge complex (C A Semeniuk 2007). They began as α dune slacks but are now stranded inland, and have accumulated 0.5–1.0 m of calcilutite. They are no longer in the dune slack environment. They comprise seasonally waterlogged and seasonally inundated basins, vegetated by rushes, sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Beach ridge swales, Busselton

The southern central beach ridge complex at Busselton (Searle & Semeniuk 1985), 5000 years old, has linear swale wetlands (Semeniuk *et al.* 1989). They began as α dune slacks but now are stranded inland, and have accumulated up to 0.5 m of peat. They are no longer subject to coastal processes. They are vegetated by rushes,

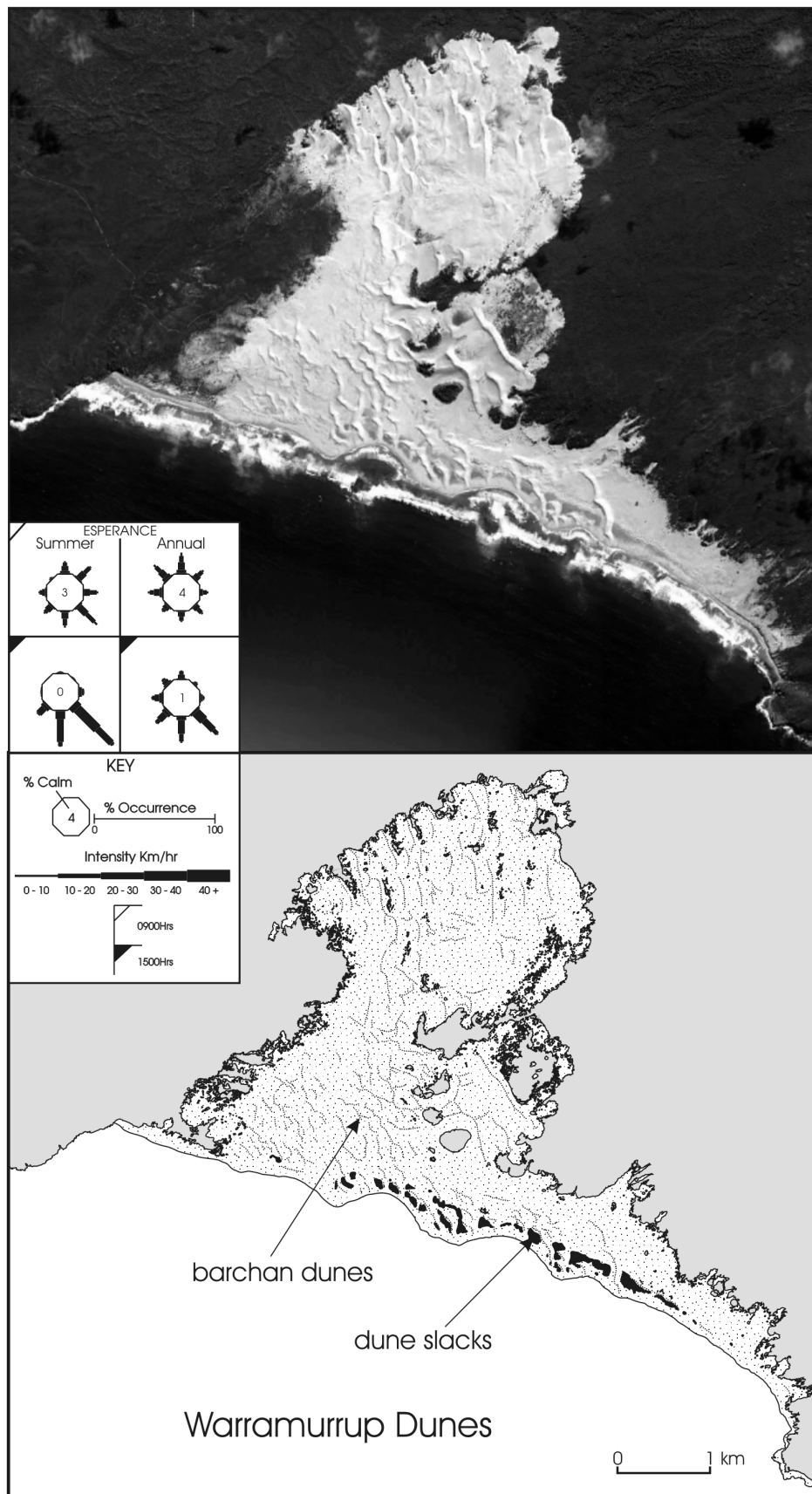


Figure 12. The Warramurrup Barchan Dune field. Aerial photograph shows the erosional inland ingressing dune field at Warramurrup, and the map shows location of β dune slacks in the mobile dune terrain proximal to the coast. Inset shows wind rosettes for the region from Esperance data.

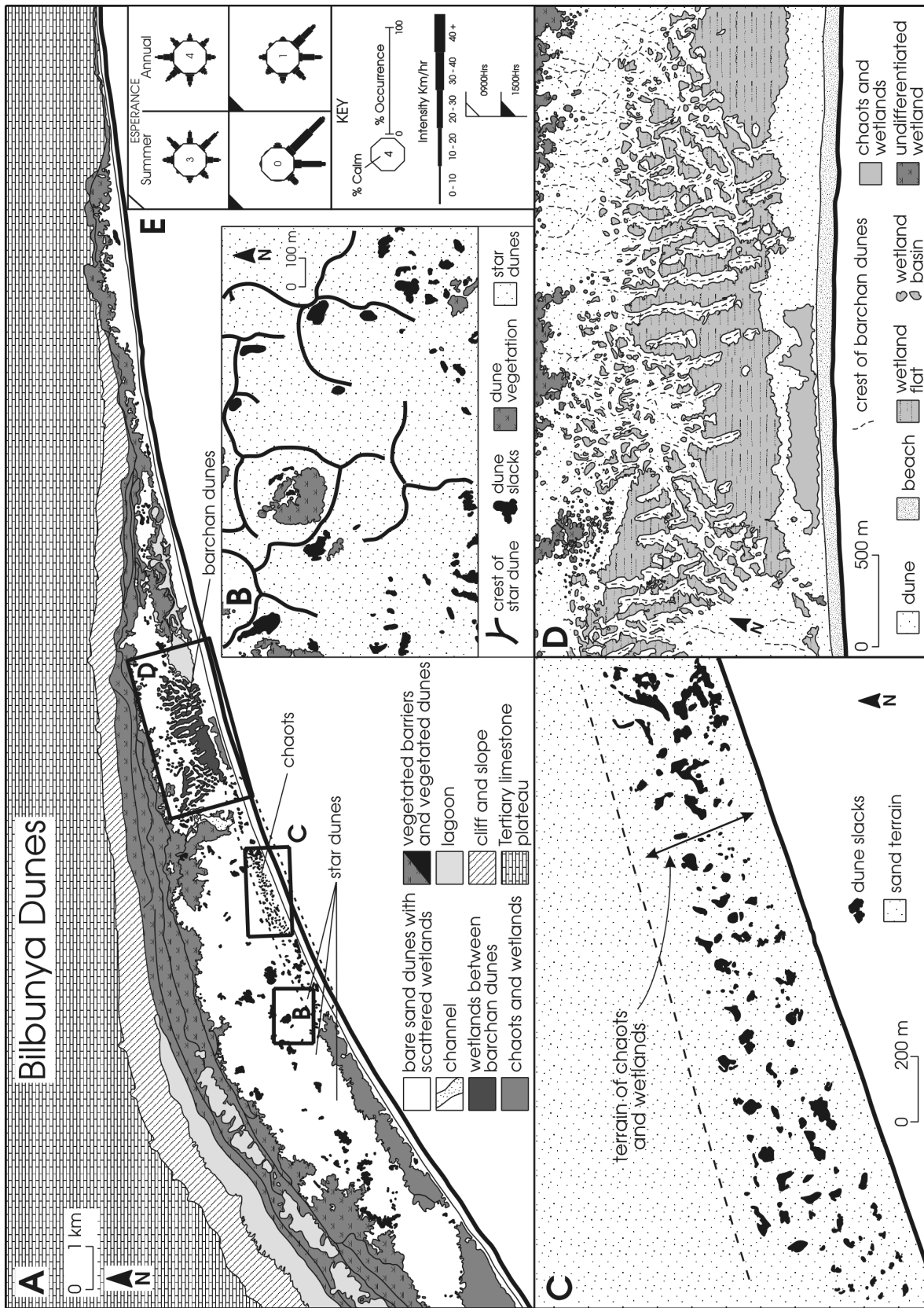


Figure 13. The Bilbunya Dune system. A. Overview of the Bilbunya Dunes showing location of the star dunes, the barchan dunes and the chaot dune terrain that are host to dune slacks. B. The star dune system with dune slacks in the star dune inter-arms. C. The chaot dune terrain with dune slacks in the hollows and depressions. D. The chaot dune system with dune slacks in the inter-dune flats and depressions. E. Wind rosettes for the region from Esperance data.

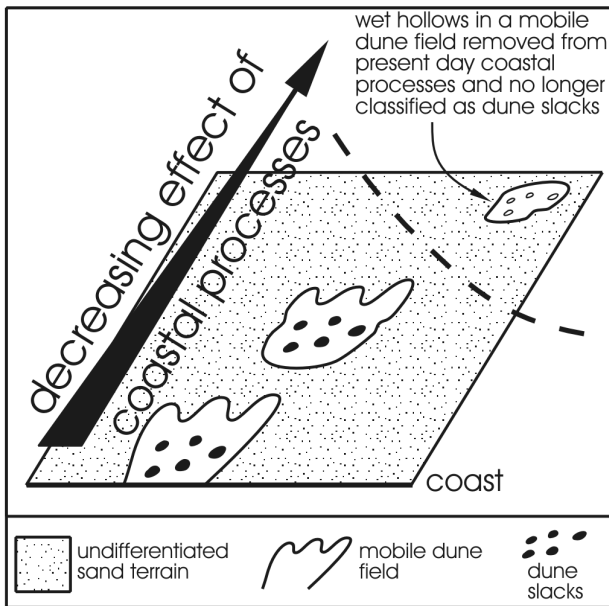


Figure 14. Idealised diagram showing the boundary between a dune system experiencing coastal processes and forming dune slacks, and an inland dune system and wetlands but no dune slacks owing to the decrease in the effect of coastal processes.

sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Chaot dune terrain, Prevelly

Inland of the coast at Prevelly, there are former chaot dunes. The lowland and depressions of this terrain were formerly β dune slacks, but now are relict, and have accumulated up to 0.75 m of peat. They no longer

function as dune slacks. They are vegetated by rushes, sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Beach ridge swales, Albany

The Vancouver Peninsula (a tombolo), south Albany, comprises beach ridges and linear swale wetlands, waterlogged or inundated by seasonal fresh groundwater rise. The wetlands began as α dune slacks but are stranded from coastal processes, and have accumulated 0.5 m of peat. Younger former dune slacks are vegetated by sedges and paperbarks; older former dune slacks are vegetated by sedges, with peripheral low shrubland. The wetlands have developed to the stage that they are no longer in the dune slack environment, subject to coastal processes.

Where dune slacks are not developed and why

There are many locations along coastal Western Australia where there are mobile dunes, inland ingressing dune fields, or a major field of parabolic dunes, but without development of dune slacks. The areas are: northern Dampier Peninsula, Tubridgi Point, Bejaling Beach Ridges, Faure Island, Edel Land parabolic dunes, Jurien beach ridges, parabolic dune fields between Jurien Bay and Whitfords, parabolic dune fields of the Leschenault-Preston Barrier, parabolic dune fields between Bunbury to Busselton, parabolic dunes along the seaward Scott Coastal Plain, parabolic dunes along the coastal D'Entrecasteaux area, parabolic dunes of the Circus Beach Barrier, parabolic dunes of the Bellanger Barrier, parabolic dunes, west of Bremer Bay, parabolic dunes, west of Esperance, and parabolic dunes, east of Esperance. This section explores the reasons why dune

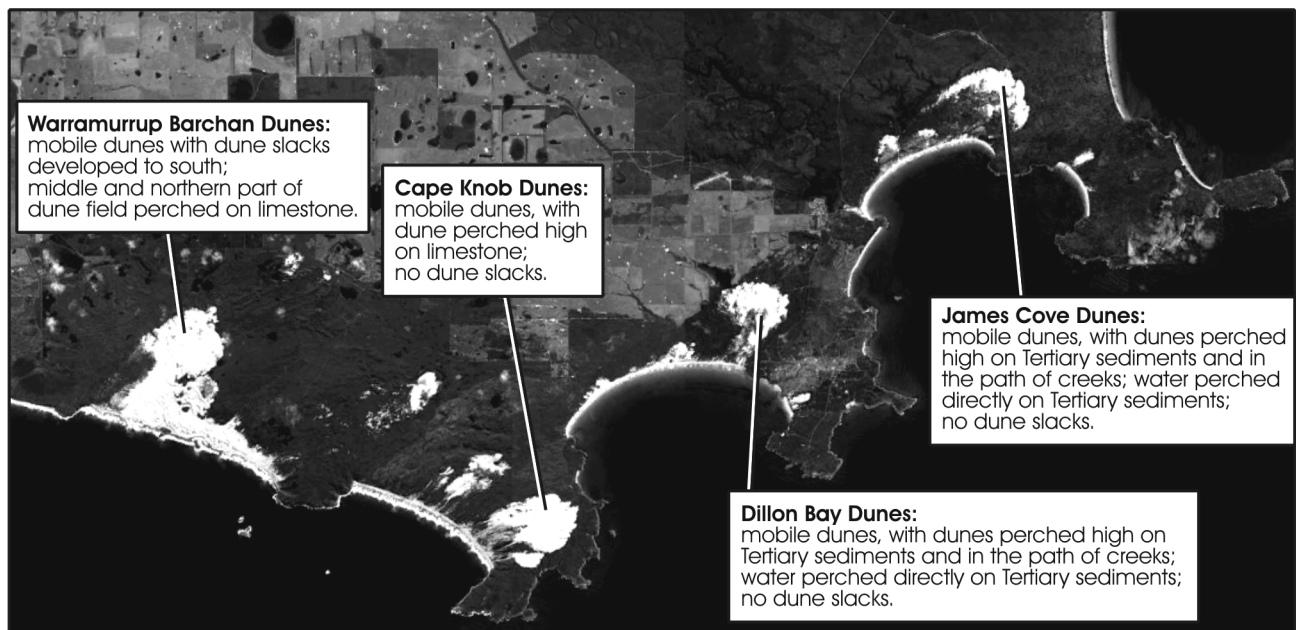


Figure 15. Aerial photograph of the Bremer Bay area showing four mobile inland ingressing dune fields but with dune slacks developed only on the Warramurrup barchan dune system. The other dunes are perched high on limestone or on Tertiary sediments, and while for the Dillon Bay dunes and the James Cove dunes there are wetlands in the landward parts of the dune complex, these wetlands are directly perched on Tertiary sediments and directly recharged by surface fluvial flows.

slacks are not developed. Table 2 provides description of these areas in terms of coastal and stratigraphic setting, and sets out why dune slacks are not developed.

In most areas, one or more of the following reasons explain the lack of dune slack development: 1) lack of seasonally dominant onshore winds; 2) dunes and the wind-excavated dune bowls are too high above the water table; 3) there is an impedance to seasonal groundwater rise; 4) dunes are perched on Precambrian rock, Tertiary sediments of the Plantagenet Group, or on Pleistocene limestone, and excavation of the dune bowl exposes bedrock or limestone well above the water table, and 5) the dune bowls are tidally influenced, or are excavated to underlying tidal deposits.

Discussion

Using Western Australian coastal variability, and the basic tenet of 'what constitutes a dune slack', we have developed an expanded definition of dune slack geomorphology, hydrology, and hydrochemistry. Study of coastal geomorphology has resulted in identifying both Holocene erosional and depositional settings where coastal processes are still active in influencing dune slack formation and function. The notion of a dune slack has been broadened to encompass all coastal dune systems, whether they are marginal to marine systems, estuaries, large lakes, or "inland seas".

The main hydrological processes, associated with dune slacks, such as seasonality and water table rise, have been retained, but the means by which these take place have been expanded to include locally mounded and perched groundwater, as long as coastal dune processes interact with the groundwater systems to form wetlands.

Dune slack hydrochemistry derives from parent dune geochemistry, the wetland fills, and climate. Hence, coastal dune systems, in various stratigraphic contexts with different parent sand geochemistry and different climate regimes, exhibit different water salinities and hydrochemistry. Climate also affects plant biogeography and productivity, so that dune slacks along the Western Australian coast sustain varying plant assemblages and biodiversity. Vegetation contributes variable amounts of organic matter to wetland fills (from enriching the wetland substrates in organic matter to the formation of peat), which can shift dune slack waters from alkaline to acid, and, for carbonate-bearing sands, change carbonate-rich substrates to carbonate-depleted substrates. Dune slacks and former dune slacks cross several plant biogeographic zones and major climate zones (Gentilli 1972; Hopper 1979; Beard 1980; Thackway & Cresswell 1995; Lyons *et al* 2000; Myers *et al* 2000; Hopper & Gioia 2004; *Environment Australia* 2007), and these provide an interesting framework within which to study the spatial variation in dune slacks, their biological diversity, and their evolution to coastal inland wetlands.

Compositional variability of sands along the extensive Western Australian coast necessitates adjusting notions of sand composition as the basis for dune slack maturity, since the sands range from carbonate-rich to quartz-rich without any implication that they represent stages in dune slack development. Based on overseas models and perceptions, some parent sands for dune slacks in Western Australia would be categorised into specific "maturity classes" before they have even begun pedogenically and diagenetically evolving. The locally developed opaque (and heavy) mineral suites of coastal sands of Western Australia add complexity to the understanding of pedogenic and diagenetic evolution of

Table 2

Locations where there are dune fields but no dune slacks

Location	Coastal and stratigraphic setting	Why dune slacks are not developed, or why wetlands are not dune slacks
northern Dampier Peninsula	dunes are reworked middle Holocene barriers (Semeniuk 2008) forming massive vegetation-free dune fields; dunes encroach landwards over tidal flat sediments	the aeolian excavations expose underlying tidal sediments, which perch rainwater; some of the dune bowls are in hydraulic contact with tidal creeks
Tubridgi Point	dunes are reworked delta deposits and desert sand (Semeniuk 1996) forming large vegetation-free dune fields; dunes encroach landwards over tidal flat sediment	aeolian excavations expose underlying tidal sediment which perches rainwater; some of the dune bowls are in hydraulic contact with tidal creeks
Bejalng Beach Ridges	northern part of Gascoyne Delta (Johnson 1982) that bars southern end of Lake McLeod	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
Faure Island	local coastal erosion, and aeolian reworking and transport of Pleistocene Peron Sand (Logan 1970) forms modern ingressing parabolic dunes (Nilemah Sand; Logan 1970)	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
Edel Land parabolic dunes	Pleistocene Tamala Limestone (Logan 1970) of mainly lithified parabolic dunes; local aeolian reworking of semi-lithified sand forms into modern ingressing parabolic dunes	Pleistocene lithified parabolic dunes, even if their bowls intersect the water table, are outside the scope of 'dune slack' environments as they are fixed and not Holocene features; the modern parabolic dunes and their bowl excavations are too high above water tables to form dune slacks

Table 2 (cont.)

Location	Coastal and stratigraphic setting	Why dune slacks are not developed, or why wetlands are not dune slacks
Jurien beach ridges parabolic dune fields, Jurien Bay to Whitfords	Holocene prograded beach ridge plain Holocene dune fields perched on Pleistocene limestone	swales do not intersect the water table bowls of parabolic dunes are excavated to basement limestone
parabolic dune fields, Leschenault-Preston Barrier	dune barrier with eastward migrating parabolic dunes (Semenuik & Meagher 1981a)	bowls of parabolic dunes are excavated to a calcrete sheet formed above the water table (Semenuik & Meagher 1981b); bowls therefore do not intersect water tables and hence no development of α dune slacks
parabolic dune fields, Bunbury to Busselton	dune barrier with eastward migrating parabolic dunes (Semenuik & Meagher 1981a; Searle & Semenuik 1985)	bowls of parabolic dunes are excavated to calcrete sheet formed above the water table (Semenuik & Meagher 1981b); bowls therefore do not intersect water tables
parabolic dunes, seaward Scott Coastal Plain	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
parabolic dunes, seaward D'Entrecasteaux area	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks; locally dune lakes are present
parabolic dunes, Circus Beach Barrier	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks; wetland on the barrier is a dune lake
parabolic dunes, Bellanger Barrier	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
series of parabolic dunes, west of Bremer Bay (<i>i.e.</i> , Cape Knob Dunes, Dillon Bay Dunes, and James Cove Dunes)	inland ingressing parabolic dune fields encroaching on Precambrian rock headlands, or Pleistocene limestone, or Tertiary plateau	dune bowls expose underlying rocky basement and water is perched directly on rock and wetlands develop; the system is not a dune slack environment (Figure 15)
parabolic dunes, west of Esperance	inland ingressing parabolic dune fields encroaching on Pleistocene limestone	dune bowls expose underlying limestone and soils; where water is perched, the terrain is moistened but wetlands are not developed; the system is not a dune slack environment
parabolic dunes, east of Esperance	inland ingressing parabolic dune field, with erosion exposing cemented sheet of beach sand some 2 m above present sea level; wind erosion incising the cemented sheet formed a terrain of small mesas; the surrounding lowlands are windows to a water table	the wetlands exposed between the small mesas are in a fixed erosional topography and not a mobile dune system; as such, this system, though in a parabolic dune terrain, is not a dune slack environment
chaots and parabolic dunes, Dunn's Creek, Cape Arid area	chaot dune terrain and local parabolic dunes that bar Dunn's Creek which meanders, bifurcates, and winds through the dune field; the lowlands are wetlands	wetlands between the dunes are mainly recharged by fluvial surface water but also are partly windows to a water table elevated by fluvial input; though in a dune terrain, the wetlands are not in a dune slack environment

dune slacks, as there will be an inherent content of Fe, P and other elements in "immature" sediments and soils. Parent sand composition will partly determine the pH of dune slack water (C A Semenuik 2007), a factor generally not addressed in studies overseas, though pH of dune slack water is a factor used to assess the "maturity" of a dune slack.

Importantly, this paper has set limits to where dune slacks cease, based on coastal processes and wetland processes. Coastal dune settings themselves will evolve with further erosion or progradation of the coast, and

there is the potential for former stranded, stabilised and vegetated dune fields to become reactivated as they, in turn, front the coastline as part of ongoing coastal erosion. There is equally the propensity for coastal progradation to occur where seaward barriers form, or where sand supplies locally increase, due to deposition at a site or across the path of along shore coastal drift.

Coastal dune wetlands, if they are undisturbed, can evolve into more independent wetlands, with internal mechanisms of recharge becoming more pronounced than the previous open through-flow systems, altering

wetland hydroperiods, and causing adjustments in sedimentary deposition style, diagenesis, hydrochemistry, and plant responses. When this occurs, it is considered that the phase of dune slack maintenance and evolution has ceased, and a more complex wetland type is developing. To provide guidance in recognizing the limits of dune slack development, this paper describes where there are the dune slacks, where there are former dune slacks, and why dune slacks are not developed in a variety of other coastal dune fields.

On a final note, this paper, with its geomorphic, hydrologic, and hydrochemical approach to dune slacks at sub-continental scale provides, in combination with biogeography and regional biodiversity of Western Australia, a structure for developing a regional and local habitat framework for plant assemblages of dune slacks of Western Australia.

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